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The Life and Death of Stars

Course Guidebook

Professor Keivan G. Stassun
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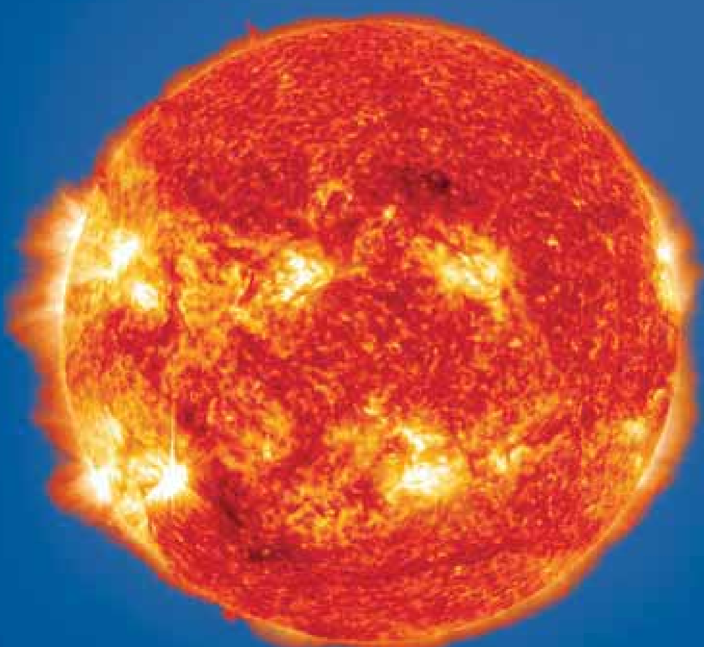

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Professor Keivan G. Stassun is Professor of Physics and Astronomy at Vanderbilt University. He earned A.B. degrees in Physics and Astronomy as a Chancellor's Scholar at the University of California, Berkeley, and was selected valedictorian of his graduating class in 1994. He earned his Ph.D. in Astronomy in 2000 as a National Science Foundation (NSF) Graduate Research Fellow at the University of Wisconsin–Madison. His dissertation research focused on the birth of stars. Professor Stassun then served as assistant director of the NSF Graduate STEM Fellows in K–12 Education Program. This program connects graduate students in science, technology, engineering, and mathematics (STEM) with K–12 schools, both to enhance science teaching and to provide leadership development for future college and university faculty. Professor Stassun served for two years as a postdoctoral research fellow with the NASA Hubble Space Telescope Program, studying newborn eclipsing binary stars, before joining the faculty of Vanderbilt University in 2003. He also holds the title of Adjunct Professor of Physics at Fisk University.

Professor Stassun's research on the birth of stars, eclipsing binary stars, exoplanetary systems, and the Sun has appeared in the prestigious research journal *Nature*, has been featured on NPR's *Earth & Sky*, and has been published in more than 100 peer-reviewed journal articles. In 2007, the Vanderbilt Initiative in Data-intensive Astrophysics (VIDA) was launched as a $4 million pilot program in astro-informatics, with Professor Stassun as its founding director. He served as chair of the Sloan Digital Sky Survey exoplanet science team, is a member of the Large Synoptic Survey Telescope executive committee, and served on the National Research Council's Decadal Survey of Astronomy and Astrophysics.

Professor Stassun is a recipient of the prestigious CAREER Award from NSF and a Cottrell Scholar Award for excellence in research and university

teaching from the Research Corporation for Science Advancement. In 2013, he was named a Fellow of the American Association for the Advancement of Science. Professor Stassun is also a national leader in initiatives to increase the number of underrepresented minorities earning doctoral degrees in science and engineering and a founding director of the Fisk-Vanderbilt Master's-to-PhD Bridge Program. In 2010, Professor Stassun served as an expert witness to Congress in its review of promising approaches for increasing American competitiveness in science and engineering. Today, he is a member of NSF's Committee on Equal Opportunities in Science and Engineering.

Professor Stassun's work has been published in several scholarly journals, including *The Astronomical Journal*, *The Astrophysical Journal*, the *American Journal of Physics*, and *Astronomy & Astrophysics*. He also serves as host for *Tennessee Explorers*, produced by Nashville Public Television, which highlights the lives and work of scientists and engineers in Tennessee to help inspire the next generation of scientific explorers. ■

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The Life and Death of Stars

Scope:

The stars have always held a special place in the human experience and imagination. We look up at the night sky and behold their beauty—we even sing nursery songs about them and wonder what they are. While we know that our own Sun's light and warmth are essential to life on Earth, too often we regard the stars with a cold, distant remove. Yet we have much in common with the stars. Like us, stars are born, live out their lives, and then die. Like us, the lives and deaths of stars represent a circle of life, the ashes of dead stars becoming the raw material for new generations of stars and their systems of planets. And, most importantly, like us, the lives of stars can be seen as having a purpose, which is to wage a life-and-death struggle against the crush of gravity and, in the process, to transform the simplest elements in the universe into the full diversity of elements in the periodic table, upon which our lives and all of the material world around us depend. Indeed, not only are we like the stars, but we are also of them.

This course will tell the incredible story of the lives and deaths of stars. You will trace the arc of the stars' lives, from their births in gigantic nebulae of glowing gas and dust, stellar nurseries; to their "life's work" as stars in middle age, like the Sun; to their fiery deaths as planetary nebulae or supernova explosions. You will examine the bizarre corpses left behind by dead stars, including white dwarfs—diamonds in the sky—as well as neutron stars and black holes, representing the densest and strangest forms of matter in the universe. You will see how the ashes of dead stars are recycled into the next generation of stars, these newborn stars enriched thanks to the previous stellar generations in the types of elements that permit the formation of planets and of life on those planets. You will look at stars in isolation, like our Sun, as siblings influencing one another's future life course and as extended families called star clusters. To gain additional perspective on the stellar life cycle, you will also study the so-called brown dwarfs, stillborn stars representing what happens when the stellar birth process fails. And by examining current theories for the very first stars that populated the universe, you will see how the stellar life cycle got started in the first place. Bringing

the story closer to home, the course will look at the magnetic nature of stars and how the Sun's magnetic storms can directly impact us here on Earth.

As a unifying theme for the course, you will take a physical perspective on the stellar life cycle, emphasizing how stars serve as agents of alchemy by which matter in the universe has been transformed from the simplest element, hydrogen, into the elements that matter most to us as carbon-based, oxygen-breathing, calcium-boned, iron-blooded life-forms. To understand these behemoths, stars, you will go down to the atomic level—both because what stars do in their furnaces is an atomic process and because our only means for studying them is to decode the information that's encoded in light, the information bearer of the stars. You will learn about the telescopes and instruments that astronomers use to collect and decode that light. You will also come to see the stars as living entities. By thinking of a star as more than merely an inanimate object, you are able to see our connection and relationship to the stars more clearly and fully. There is a beauty to thinking of stars not just in terms of physics but also in terms of their purpose, a purpose to which humans have always, and always will, relate. ■

Why the Stellar Life Cycle Matters

Lecture 1

In this course, you will learn about the various stages of a star's life, from birth to death and back to birth—its life cycle—in detail. This lecture will begin by looking at the life cycle of a star in broad strokes, giving you the sweeping narrative of stellar life before the course zooms in on each fascinating feature. We now understand the stars from a physical perspective—not as mere lights in the sky, but as engines of matter, energy, and of the raw material of life itself.

The Life Cycle of a Star

- The birth of a star is a process that takes place within what we call stellar nurseries, which are enormous clouds of gas and dust that float through our galaxy, weighing tens of thousands of times what our Sun does. Within these massive nurseries, hundreds or thousands of stars can be birthed all at once.

- Gravity causes the onset of stellar birth within these gigantic clouds; it causes slightly denser portions of the cloud to fall in on themselves, generating an even denser region that then begins to collapse even faster. This runaway collapse process creates heat, so the embryonic star—called a protostar—begins to glow.

- The stellar birth process begins in these very dense clouds of gas and dust. After a few hundred thousand years, though, the cloud becomes increasingly incorporated into the fledgling stars themselves or else eroded away by the intense glare of the most massive stars that have ignited within the stellar nursery. At this point, the cocoons of individual stars become sufficiently exposed to be seen directly.

- The word "proplyds" is astronomers' shorthand for stars with protoplanetary disks, which are disks of gas and dust from which planets around stars are made. As seen through a telescope,

proplyds are individual cocoons swimming in a sea of irradiated gas and dust, each one containing within it a new star encircled by the material from which its solar system of planets will be made.

- After about 10 million years, a star reaches adolescence. At this point, the star is fully exposed and is generating its own heat and light to warm and illuminate the entourage of planets that will encircle it.

- Next, the star enters a long, stable period of middle life. For a star like the Sun, this middle life stage lasts a very long time—about 10 billion years. And during all of that time, not much happens—at least nothing terribly dramatic.

- But in reality, it is during this time of adulthood that the star is slowly, patiently, and steadily doing its life's work. Deep in its core, the mature star sustains the process of nuclear fusion. The ongoing fusion reactions allow the star to create light and heat, which allows the star to wage a lifelong struggle against the inexorable crush of gravity.

- And in the process, it is performing the magic of alchemy—converting the simplest and most abundant element, hydrogen, into the other elements of the periodic table. An adult star fabricates new elements, such as carbon and oxygen and calcium and even iron, and it holds these elements in store until its death. At that point, it will give up these elements for the next generation of stars and planets and, potentially, their inhabitants.

- The stellar death is a quiet but dramatic one, as the star slowly disembodies itself, puffing off shells or rings of itself into the surrounding space as a so-called planetary nebula, which is the enduring legacy of a dead star.

- Stars can also end their lives more explosively as a supernova. These immense explosions, if several of them should go off in the same nearby region of the galaxy, can produce geysers of material that spew out above the disk of the galaxy and then rain back down into the galaxy.

- Thanks to the alchemy that those stars performed during their lives, this material, cascading down, has been enriched with heavier elements than what the exploding stars began with. Therefore, a new generation of stars in the galaxy inherits this material, and both the newborn stars themselves and the planets that form around them can now incorporate the types of elements that make life as we know it possible.

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The open star cluster Pleiades is about 430 light-years from the solar system.

Types of Stellar Clusters

- Most stars are, in fact, not born single; rather, they most often are born with at least one sibling. Sibling stars grow up with one another and orbit one another through life and death. Indeed, in some cases there can be three or more sibling stars orbiting one another, and they are more present than you might think.

- Indeed, stellar siblings affect one another in important ways. If they get too close, a dramatic sibling rivalry can ensue such that, through the stars' disruptive gravitational influence, one or more of the stars can be prevented from forming solar systems. Even after death, the siblings can interact, as sometimes a living sibling will cause a dead sibling to reignite briefly but spectacularly in a special and important type of supernova explosion.

- Beyond having siblings, stars are also born into larger extended stellar families, which we call star clusters. There are two main types of stellar clusters. One type is called a globular cluster, which are massive, tight-knit stellar families with tens of thousands or even more members. These are also ancient families, left over

from the formation of our galaxy. Because these families have so many members, their mutual gravitation attraction has been strong enough to keep these families together over the eons since our galaxy's beginnings.

- The other type of star cluster is what we call an open cluster. A good example of an open cluster is the Pleiades, or Seven Sisters. In fact, the Pleiades cluster has several hundred stellar members. These open clusters represent more modern stellar families, having formed in their stellar nurseries more recently than globular clusters. Unlike the globular clusters, open clusters do not have sufficient gravity to keep the stars together, so the stars in these families eventually drift apart.

The Elements of Life

- We can think of a star's purpose in life as being the creation of the elements that make all of life possible. The most abundant element in the universe—making up about 75% of matter in the universe and, therefore, 75% of the matter in stars—is the simplest element: hydrogen. Hydrogen is present in most of the compounds that we know, but on its own, hydrogen doesn't do anything, and you can't make anything out of just it. However, stars are made mostly of hydrogen and, over their life cycle, use it to make all of the other elements.

- The next element in the periodic table is helium. The matter in the universe started out as 75% hydrogen and 25% helium, and almost nothing else. But ever since the big bang, all of the new helium that has been created in the universe has been made by stars like the Sun, synthesized from hydrogen through the power of nuclear fusion.

- This relatively simple conversion of hydrogen to helium is the main process through which stars generate the light and heat that they will produce throughout their lifetimes. Stars are nuclear factories, using fusion to manufacture heavy elements from the lighter ones.

- Carbon is the most fundamental element in all of life. Every living cell, every organic compound, contains it as its building block. And every single carbon atom in the universe was created by stars like the Sun, synthesized from helium atoms. Without the stars, there would be no carbon, and without carbon, there would be no life.

- Oxygen is what we breathe, and it's also in every drop of water, so it's essential to life as we know it. Every atom of oxygen in the universe was created by stars, synthesized in their cores from carbon and helium atoms. The process of making oxygen atoms occurs as one of a dying star's final breaths. And in those dying breaths, stars make the stuff that we breathe to live.

- Silicon has become central to our technologically built world, and every silicon atom in the universe was created by stars.

- Sodium, phosphorus, potassium, and calcium are in things like salt and chalk, but they are also minor but critically important components in our blood, central to innumerable processes constantly at work in our bodies. Each of these elements, and indeed every single atom of them in the universe, was made by stars as they approached the ends of their lives.

- In our everyday experience, we regard iron as something so substantial and associated so strongly with the Earth that it may be difficult to imagine it in the context of a luminous being like a star. But, indeed, every atom of iron has been forged in the cores of stars. In fact, iron is special because it is the last element that a star can synthesize from lighter elements before conceding defeat to gravity.

- Copper, zinc, and iodine all play a role in our bodies, and all of these elements were also made by stars—or, rather, in the fiery explosive supernova deaths of massive stars.

- Altogether, the life cycle of stars is the universe's process for transforming the simple, basic matter with which the universe began—

hydrogen and helium—into the variety of elements that make life possible and almost every aspect of the world we've built around us.

The Importance of Stars

- Our connection to the stars is a profound one. We are made of the ashes of long-dead stars, ashes that represent the laborious effort of a behemoth struggling in a fight to the death with gravity. Interestingly, this connection to the stars is something humans have always seemed to sense—even before scientists understood the true physical nature of the stars and why they do what they do.

- Throughout human history, all civilizations have gazed on the stars and constructed mythologies to explain the apparent patterns—the constellations. There has always been an innate understanding that the stars, whatever they might be, are important.

- As fantastic as these mythological stories may have been, constellations are not real. In 3-D space, most stars that look to us like they're in the same constellation are actually thousands of light-years apart, and if we could view the night sky from a different angle, we'd see a whole different set of "constellations." So there are no patterns in the stars beyond those that people imagine are there.

Suggested Reading

O'Dell, *The Orion Nebula*.

Smith, Stassun, and Bally, "Opening the Treasure Chest."

Questions to Consider

1. What are the parallels—literal and metaphorical—between the life cycle of the stars and that of human life?

2. Were the mythological conceptions of the stars by early human societies "wrong," even if not physically accurate?

The Stars' Information Messenger

Lecture 2

In this lecture, you will learn that light is the ultimate information bearer of the stars. Imprinted in the light we receive is crucial information—quantifiable information—about the stars: their brightnesses, their temperatures, their motions, and their elemental compositions. The ability to sense the stars and everything about them with nothing more than light is foundationally important to everything that you will learn about throughout the rest of this course.

How Light Interacts with Matter

- The Sun appears yellowish to our eyes, but in fact it emits light of all colors. Scientists can create a light spectrum of sunlight by spreading out the Sun's intrinsic rainbow of light into its constituent colors. When we look at this spectrum, we see all of the colors that we know—from red at one end to purple, or violet, at the other. The yellows and greens are the brightest colors (which is why the Sun mainly looks to be that color), but overall, we see a smooth, continuous rainbow of many colors.

- However, we also see a curious pattern of very specific colors that are "missing" from the Sun's spectrum. These show up as dark patches in the spectrum. In other words, we see specific colors that have been absorbed from the Sun's otherwise continuous spectrum.

- There are essentially four ways that light and matter interact: emission, absorption, transmission, and reflection. Emission refers to the process by which light is produced by an object—whether it is a solid, liquid, or gas. Essentially, emission is the radiance, or "glow," of an object. All things glow, just not necessarily in ways that we can see with our eyes. The Sun is an example of an object that does emit light we can see. And that light, when it reaches the Earth, interacts with the things it encounters.

- Some things absorb the sunlight and heat up as a result. Other objects are transparent to the light—such as a windowpane—so we say that the light is transmitted through it. Still other objects reflect the Sun's light, which means that the light "bounces" off the object.

- Most things do a combination of these things. For example, they might absorb some of the light and reflect the rest. Most of the things around us that have colors that we see are not actually glowing that color; rather, they absorb most of the colors that are present in the light they receive and only reflect certain specific colors.

- Whatever color an object reflects is the color our eyes perceive. For example, the green leaves on a tree appear green not because they are glowing that color; rather, they appear green because the chlorophyll in the leaves absorbs the reds and the yellows from the sunlight and reflects only the greens and the blues.

Properties of Light and Wave-Particle Duality

- Light has a very peculiar nature, which is referred to as its wave-particle duality. This means that we can equally think of light as being like a wave or as a particle. In some cases, it will be more helpful to talk about it as a wavelike phenomenon—like sound—and, in other cases, it will be more helpful to describe it as if it were a discrete particle—like an electron.

- The wavelike version of light can be thought of as being similar to waves in water. If you drop a pebble into a pond, the water's surface is disturbed, causing it to undulate up and down where the pebble plopped in. From that point, those undulations travel outward in all directions—they propagate—and they do so with a characteristic speed and with a characteristic distance between successive undulations.

- We refer to the distance between undulations as the wavelength of the wave. With the wave traveling outward at a certain speed, and with a characteristic wavelength between successive waves, we can also define a frequency—the rate at which the waves pass by a fixed

point. A good analogy for this is waves in the ocean washing up to shore. The distance between successive swells is the wavelength. Those swells move toward the shore with a certain speed. When the waves reach the shore and crash down onto the beach, they do so with a steady cadence—the frequency of the waves.

- For any wave phenomenon, including waves at the beach, there is a specific relationship between the wave's speed, wavelength, and frequency. For light, the speed is the speed of light, which is a fundamental constant of nature.

- Because the speed of light is constant, that means that a light wave's frequency and wavelength are always inversely related. In other words, a light wave of a higher frequency has a shorter wavelength, and a light wave of a lower frequency has a longer wavelength. Think again about the waves at the beach. If the swells are close together (short wavelength), successive waves will arrive at the shore with a higher cadence (higher frequency).

- Just as our ears perceive different frequencies of sound waves as different pitches of sound, our eyes perceive different frequencies of light as different colors. Higher-frequency light (or shorter-wavelength light) is blue, while lower-frequency light (or longer-wavelength light) is red.

- Just as there are other fundamental particles in nature—like protons and electrons—light can be thought of as a discrete particle, which we call a photon. And as a discrete particle, light carries a discrete amount of energy. This energy, it turns out, is directly related to the light's wavelike properties. Higher-frequency, shorter-wavelength photons carry more energy, and lower-frequency, longer-wavelength photons carry less energy. Blue light is more energetic, and red light is less energetic.

The Electromagnetic Spectrum

- Light comes in different varieties, what we ordinarily think of as color. But the colors that we're familiar with from everyday life

are just a tiny sliver of a much larger range of colors that exist in nature. The full range of colors, including those invisible to our eyes, is what we refer to more generally as the electromagnetic spectrum of light.

- The part of the electromagnetic spectrum that we can see is referred to as the visible part of the spectrum, and it contains the red-to-violet rainbow. The wavelengths of light that are responsible for that band of visible colors are typically about 1 micron in length, or about the size of a bacterium.

- But light comes in an infinite range of other wavelengths, both shorter and longer than those we can see. Ultraviolet light has wavelengths that are just a little bit shorter than the deepest violet we can see. In other words, this light is "beyond violet," which is the literal meaning of ultraviolet.

- If you continue beyond ultraviolet, you come to the X-ray part of the electromagnetic spectrum. X-ray light has even shorter wavelengths and even higher energies. Beyond that, the shortest wavelengths and highest energies are the gamma rays. These photons are so energetic that on Earth they are generally only encountered in nuclear explosions.

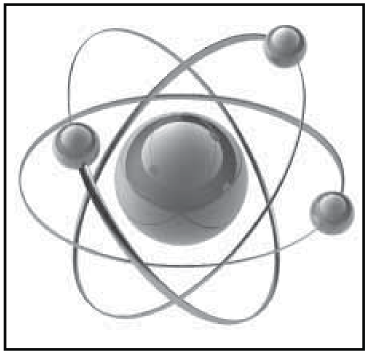
- Coming back to the visible part of the electromagnetic spectrum, there are photons with longer wavelengths as well. At wavelengths just longer than the reddest red that we can see is the infrared, meaning "below red." Infrared light is sometimes referred to as "thermal radiation," because most things that have temperatures of the kinds we experience every day glow most strongly in infrared light.

- At wavelengths longer than infrared, and at the lowest energies, are radio waves, a portion of which are called microwaves. Radio waves are photons with extremely long wavelengths, as long as a football field or even longer. In addition to its applications in radios and microwave ovens, our understanding of light's

properties enables us to build the scientific tools with which we explore the cosmos.

Properties of Matter and Atomic Fingerprints

- All atoms consist of the same basic parts: a nucleus composed of some number of protons and neutrons, orbited by a number of electrons. All of the mass of the atom is essentially contained in the nucleus, because the electrons weigh next to nothing. The number of protons in the nucleus is what determines which element it is.



An atom consists of a nucleus of protons and neutrons surrounded by a cloud of electrons.

- The simplest element is hydrogen. It is simply a proton that, in its neutral and most common state, is orbited by a single electron. We say that the orbital energy of the electron is "quantized," because it is only permitted to have energies of certain discrete quantities.

- An electron possessing the minimum permitted amount of orbital energy is in the ground energy state—its energy is at the lowest possible level. When an electron gains energy in an amount sufficient for it to have one of the higher permitted energy levels—suppose it got bumped by another atom—then the electron is in an excited energy state or level. When that happens, the electron will, after a short time, spontaneously drop back down to the ground energy level.

- Because the electron loses energy in the course of dropping from an excited energy level to a lower energy level, that same amount of energy must be released by the atom, and it is released in the form of a photon of exactly that amount of energy. In other words, the atom emits a photon of specific wavelength, because that photon

carries away a specific amount of energy exactly equal to the amount of energy lost by the electron when it dropped down.

- Each element has a unique set of permitted energy levels for its electrons, and therefore, each element's electrons can only perform certain discrete energy jumps. Each element will emit only certain specific wavelengths of light corresponding to those discrete energy jumps. In other words, every element in the periodic table emits a distinct pattern of wavelengths of light—a unique light fingerprint.

- If you examine the light emission patterns for a few different elements, you will see how distinct each one is from the others. And because emission patterns are like fingerprints, you can tell which elements a star contains by looking at its emission pattern.

- The emission process also happens in reverse, and it provides a complementary way of identifying the presence of specific elements in a star.

- We can discern the presence of an element either from the appearance of light at specific wavelengths or from the absence of light at those specific wavelengths. In both cases—an atom emitting its light fingerprint in one case or an atom absorbing its light fingerprint in the other case—we know that atom is there because we know that only that type of atom can interact with those specific wavelengths of light.

Suggested Reading

NASA Goddard Space Flight Center, "Electromagnetic Spectrum."

Ptable, "Periodic Table."

Questions to Consider

1. How does the astronomical study of the stars differ from most other sciences, in which experiments can be performed under controlled conditions in a laboratory and in which the objects of study can be directly manipulated?

2. What is the relationship between studies of elements in chemistry laboratories and our interpretation of the light spectra of the elements from astronomical objects?

Measuring the Stars with Light

Lecture 3

The information that we glean from starlight is the key with which we can unlock the mysteries of the stellar life cycle. In this lecture, you will learn a few more essential details about the way astronomers use light to understand the physical properties of stars. Specifically, this lecture will focus on those physical attributes of stars that you will need throughout this course to truly understand the stellar life cycle.

Kirchhoff's Laws and Wien's Law

- Kirchhoff's laws are a set of physical laws that together describe the ways in which different types of objects emit and absorb light. Kirchhoff's first law describes the radiation emitted by any opaque body. It says that an opaque object emits a continuous spectrum of light at all wavelengths.

- Kirchhoff's first law states that the rainbow of light emitted by an opaque object is continuous. That means that it emits all wavelengths of light—from gamma rays to radio waves, and everything in between. That doesn't mean it emits the same amount at all wavelengths, just that it does emit some light at all wavelengths.

- One of the simplest but most important pieces of information we can glean from the stars is color. The color of light is associated with its energy. Bluer light is more energetic light; redder light is less energetic. More energetic objects emit more energetic light. Therefore, more energetic objects emit bluer, more energetic light, whereas less energetic objects emit redder, less energetic light.

- The basic measure of an object's energy is its temperature. A hotter object contains within it more energy in the form of heat—what physicists call thermal energy. A colder object contains less heat, or less thermal energy, and its temperature is lower.

- It turns out that we can quantify this relationship between color and temperature precisely. The relationship is called Wien's law, which is a simple formula that can be dissected as follows: The wavelength of the light at which an object emits most strongly—in other words, the brightest wavelength of light in the continuous rainbow emitted by the object—is a constant divided by that object's temperature. That is, the wavelength of peak light emission is inversely proportional to the temperature of the emitting body.

- The light spectrum emitted by an opaque body such as a star is continuous—some amount of light is emitted at all wavelengths, but not the same amount of light at all wavelengths. Rather, any given opaque body will emit most of its light in one part of the spectrum and less (but some) light at all other wavelengths.

- The point of Wein's law together with Kirchhoff's first law is that we have a straightforward way of determining the temperature of a star. All we have to do is measure the star's continuous light spectrum using a spectrograph attached to a telescope and record the wavelength at which most of the light is being emitted, which is nothing more than looking at which wavelength of the spectrum is brightest. Then, we can calculate the temperature of that star's emitting surface.

- Kirchhoff's second and third laws relate to nonopaque, or transparent, gases and how they interact with light. Kirchhoff's second law states that a transparent gas will emit not a continuous rainbow of light, but it will emit light at only certain discrete wavelengths. These specific, discrete wavelengths of emission correspond to the energy levels in the atom that its electrons are permitted to jump between.

- This means that each type of atom in a gas—each element—emits a distinctive fingerprint. It emits only certain wavelengths of light, and that pattern of light emission is unique to that element.

- Kirchhoff's third law states that a transparent gas, when exposed to a continuous spectrum of light, will absorb a specific, discrete set of those photons. It will be the same wavelengths of light that this gas would emit in the Kirchhoff's-second-law scenario. The only difference is that, whereas in Kirchhoff's second law the elements in the gas are seen in isolation, emitting their permitted wavelengths of light, in the third law we are seeing the elements against the backdrop of a bright, continuous source of white light, which the elements can absorb.

Gustav Robert Kirchhoff (1824–1887) was a German physicist who first announced Kirchhoff's laws in 1845.

- We can directly identify which elements are absorbing the light by recognizing the specific pattern of wavelengths being absorbed out from the otherwise continuous spectrum impinging on the absorbing gas.

- When we look at the light spectrum emitted by actual stars, we mainly see a continuous rainbow of light. But we also see imprinted on that continuous spectrum a set of dark absorption bands, from which we can determine the elemental makeup of the star.

The Doppler Effect

- Another essential piece of information we can learn about a star from its light spectrum is its motion. All stars in our galaxy move relative to one another. The stars orbit about the center of our galaxy. In addition, pairs of stars are often orbiting one another—what we call binary star systems—and we can learn still more by studying those motions.

- The astronomer’s basic tool for measuring the speed of a star’s motion is the Doppler effect, which was first studied in the context of sound waves, which in their physical behavior bear some similarities to light waves. The effect states that when an object is moving toward you, the emitted waves are bunched up and register as a higher frequency. When an object is receding from you, the emitted waves are stretched out and register as a lower frequency.

- The light waves emitted by an approaching object are bunched together, which we register as a higher frequency of light, which means a higher energy, or bluer color of light. Conversely, the light waves emitted by a receding object are stretched, which we register as a lower frequency of light, which means a lower energy, or redder color of light. The color of the light is shifted, to the blue or to the red, depending on whether the object is moving toward or away from us.

- The Doppler effect has a formula associated with it that allows us to precisely calculate the speed of a star from the exact amount by which its light spectrum has been shifted. The formula says that the percentage by which the star’s wavelengths are shifted is the same as the percentage of the speed of light that the star is moving.

Measuring Luminosity and Parallax

- The total intrinsic light output of a star is its luminosity. A star’s luminosity together with its temperature allow us to piece together its entire life cycle and to pinpoint exactly where in its life cycle a given star is at any moment.

- In principle, measuring the intrinsic luminosity of a star is simple: Just measure how bright it appears, measure how far away it is, and adjust its apparent brightness for its distance. How bright something appears depends both on how bright it actually is and how far away it is.

- In fact, light obeys what is referred to as an inverse-square law: The farther away a light is, the dimmer it appears, and it gets dimmer by the square of the distance.

- The problem is that, while measuring the apparent brightness of the star is trivial, measuring its distance is generally very difficult. That's because most stars are so far away, so incredibly distant, that we have no way of getting a vantage point to sense whether they are relatively close or far.

- Fortunately, there are some stars that are nearby enough that we can use a method of triangulation, also known as parallax, to measure their distances directly. We can discern relative distances of objects by virtue of how much of a jump our brain notices between the apparent position of an object as seen by each eye. A relatively large jump means that the object is relatively close; a small jump means that it must be farther away.

- Our ability to do this is somewhat limited, however, because our two eyes are not very far apart. If they were twice as far apart, we'd be able to perceive these positional jumps half as big, allowing us to have twice the depth perception.

- We can do the same thing with the stars, now with "eyes" as far apart as the diameter of the Earth's orbit about the Sun. By measuring the amount by which the position of a star appears to jump relative to the more distant stars in a 6-month period, for example, we can directly determine its distance. Given the size of the Earth's orbit, our depth perception on the stars is pretty good, but it's not great.

- We can use this technique to directly measure the distances to stars as far away as about 1,500 light-years. That's not very far in the grand scheme of things—our galaxy is 100,000 light-years across—but it is far enough that we can measure the distances to hundreds of stars and use their properties to figure out the properties of all other stars.

- By measuring the parallax of a star, and thereby determining its distance, we can now use the brightness of the star that we see on Earth to determine its intrinsic luminosity. That luminosity and the temperature that we can measure with Wien's law allow us to determine almost everything about a star's life and death.

Suggested Reading

University of Nebraska at Lincoln, "Doppler Shift Demonstrator."

Wikipedia, "Stellar Classification."

Questions to Consider

1. What are the most important physical properties of the stars, with respect to the life cycles of stars, that we can measure using the light spectra they emit?

2. How does the actual relationship between color and temperature for physical objects, as described by Wien's law, compare to our everyday usage of colors to describe temperatures? For example, what color do you usually associate with cold, and what color do you associate with hot?

Stellar Nurseries

Lecture 4

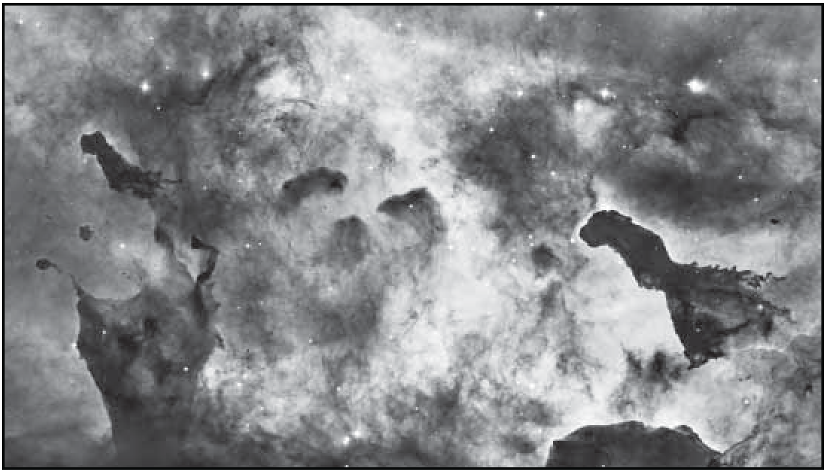
In this lecture, you will begin a detailed investigation of the places where stars begin their lives—stellar nurseries. You will learn that the properties of light can be used to infer the nature of these spectacular places. You will also learn that stellar birth is intimately connected to stellar death, as massive stars, firstborns in these nurseries, exert both a destructive and a creative influence on the surrounding clouds of gas and dust, eroding them, shaping and sculpting them, and helping to trigger the onset of stellar birth both in their immediate vicinity and across the galaxy.

The Carina Nebula

- Stellar nurseries involve enormous nebulae, clouds of gas and dust illuminated from within by a thousand forming stars, with the massive stars at the center sculpting the surrounding nursery. The process of stellar birth that is presented in this lecture is not unique to our corner of the universe; it is a general description of how stars everywhere come to be.

- In images of the Carina Nebula, one of the most striking patterns is the presence of pillar-like structures across the image. These structures do not point in random directions. Instead, they seem to be pointing up toward the top. In fact, there is something very bright at the top: Eta Carinae, which is an intensely luminous star within the Carina stellar nursery.

- Eta Carinae is a very massive star that evidently formed very early on within the larger stellar nursery. In fact, it may very well have been the first star to form here. And this firstborn of the Carina Nebula is no runt. It is one of the most massive stars in this neighborhood of the galaxy, probably weighing in at 30 times the mass of our Sun or more. It is having a tumultuous birth, its immense luminosity blowing it apart so that it is already entering its death throes.



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The Carina Nebula, containing striking pillar-like structures, is a stellar nursery.

- The bubble-like features immediately surrounding Eta Carinae, called the Homunculus, are parts of that star that are being expelled back into the surrounding larger nebula. The Carina Nebula is about 8,000 light-years away from us, so what we are witnessing in images of the Carina Nebula actually occurred 8,000 years ago. But that is a snapshot in what is a million-year-long process, so we really are watching this happen effectively in real time.

- Eta Carinae is not just blowing itself apart. The intensity and harshness of its radiation and of its powerful wind is shredding the surrounding cloud of gas and dust in the nebula as a whole, sculpting it, compressing it, driving waves of pressure through it that in turn may be serving as the trigger for the thousands of smaller stars forming throughout the nursery.

- This is a crucially important aspect of how the stellar birth process appears to work in these stellar nurseries. The early formation of extremely massive, luminous stars within the nursery, and the near immediate self-destruction of those stars, leads simultaneously

to the destruction of the gigantic cloud of gas and dust and the triggering of stellar birth throughout the nursery. Stellar life and death are intimately related from the start.

- In images of the Carina Nebula, you can see glowing wisps of material surrounding the pillar structure. This is hot, evaporated gas from the destruction of the surrounding cloud of gas and dust as it was boiled away by the intense radiation from the massive star Eta Carinae. That boiled-off gas now fills the space within the larger cloud of gas and dust that has now been evacuated by Eta Carinae. It is like a blister within the cloud, carved into the larger body of the cloud by the massive star and now filled with boiling, hot gas.

The Trifid Nebula

- Another example of a stellar nursery where you can see an expanding blister filled with hot gas is in images of the Trifid Nebula. The beautiful colors of these magnificent stellar nurseries reveal some of the major elemental constituents of the gas out of which the entire stellar nursery is made and which are, therefore, becoming incorporated into the stars as they form within.

- For example, in the Trifid Nebula, you can see the red glow of hydrogen. That is the result of hydrogen atoms in the cloud being heated by the intense radiation of the central hot star, which excites their electrons to higher energy levels. Then, as the electrons within the hydrogen atoms make a permitted jump back down to a lower level, the atoms emit a photon of a specific red wavelength.

The Orion Nebula

- When you look at images of the Orion Nebula stellar nursery, you can see a striking blue color. This is the result of oxygen atoms, ionized not just once but twice, and their electrons making a permitted jump down in energy that emits this specific color of light.

- Interestingly, it took a long time for astronomers to recognize this emission as being the result of oxygen in these stellar nurseries, because oxygen had never been seen to emit that particular color of light in the laboratory. So, early on, astronomers assumed that this must be some new element not before seen on Earth, and it was dubbed “nebulium.”

- Later, experiments showed that oxygen twice ionized can emit this particular color of light as long as the gas is extremely rarefied, which is the case in outer space. In the laboratory, it requires vacuum conditions that are very difficult to achieve, explaining why it had not been seen on Earth.

- Incidentally, a similar thing occurred with helium. The light fingerprint of that element had not been seen in the laboratory, because helium is such a rare element in Earth’s atmosphere. So, when the light fingerprint of this mystery element was first detected in a solar eclipse in 1868, it was dubbed “helium,” from the Greek word *helios*, meaning “Sun.” Of course, helium is not unique to the Sun; rather, it is in abundance throughout the universe, second only to hydrogen. Indeed, the new stars forming in these stellar nurseries are being made of fully 25% helium.

- But where are these amazing stellar nurseries found, and what do they look like before they light up as nebulae? These nurseries, in fact, begin as immense clouds of gas and dust that move through our galaxy, material gathered up by gravity after the deaths of previous generations of stars, and they appear as cold, dark clouds drifting through space.

- When we look at galaxies similar to our own, such as the Andromeda Galaxy, we see these gigantic clouds as dark swaths obscuring the light from the billions of stars shining within the disk of the galaxy. The clouds can be seen as long streams extending along the disk of the galaxy, demarcating the spiral arms that we have come to associate with galaxies such as our own.

The Milky Way Galaxy, consisting of several billion stars, is home to our Sun.

- In fact, the spiral arms of galaxies like ours represent places within the galaxy where gravity is relatively stronger, due to a buildup of mass at those locations in the form of stars, gas, and dust. The additional strength of gravity here compresses the gas and dust, forming the relatively tight streams of material that we see and within which gravity can further do its work to initiate the birth of stars.

- We can see the same types of giant clouds of gas and dust within our own Milky Way Galaxy. In fact, if you've been fortunate enough to see the sky on a dark, clear night from a remote location far from any city lights, you probably noticed the band of light stretching across the sky. And you probably noticed the dark swaths cutting through that bright band, obscuring it deeply in some places.

- Those dark swaths are the result of many giant clouds of gas and dust within the disk of our galaxy, blocking our view of distant

stars. If you study these clouds as seen in the Milky Way on a clear night sky, you'll notice a great deal of complexity and variety. Some of the clouds are long, like tendrils; some are straight and jutting; others are curved; and some appear as thin, wispy veils.

- One of the clouds, known as Barnard 72, looks like an S-shaped snake against the background of stars. It's named after the famed 19th-century astronomer and astrophotographer E. E. Barnard. In *visible* light, these clouds appear in dark silhouette against the backdrop of bright distant stars. But in *infrared* light, they appear as mammoth luminous beings all their own.

- The cloud complex in the constellation Orion is a wonderful example. In the head of Orion, we once again see the intimate connection between stellar death and new stellar birth. In this case, a massive star first born within the giant cloud has already lived out its brief, dramatic life, in the span of just a million years or so, and in its death has sculpted the surrounding cloud, weathered it and compressed it, triggering the onset of stellar birth all around its fiery grave.

- Indeed, the distribution of cloud material and the instigation of new stellar nurseries across the entire galaxy are influenced by the life cycles of giant stars. The sculpting action of the lives and deaths of massive stars on the surrounding clouds is more than a local phenomenon. The entire galaxy is influenced by these life-giving stellar deaths.

Suggested Reading

Astronomy Picture of the Day, "Stellar Nurseries."

HubbleSource, "Orion Nebula Fly-Through."

Questions to Consider

1. The most massive stars in a stellar nursery are clearly very important for influencing the birth process of other stars in the nursery and for shaping the nursery itself. Why do you suppose that the most massive stars tend to be found at the centers of nurseries?

2. What other processes can you think of in nature in which death is essential to new life?

Gravitational Collapse and Protostars

Lecture 5

Stars are born from immense clouds of gas and dust several light-years in extent, what we call stellar nurseries. These nurseries are like the neonatal ward at the hospital, with many babies being tended to all together. But, just like the neonatal ward, the individual birth of each one of those stellar babies is intimate and special, and it involves a birth process that plays out very quickly—just a few million years. While the last lecture focused on the nursery as a whole, this lecture will focus on the individual babies within the nursery.

The Formation of Protostars

- Like an obstetrician using sonograms to peer into a mother's womb, the astronomer can use infrared light to peer into the stellar womb, otherwise hidden from our view by the obscuring gas and dust from which the baby star is forming. We refer to the embryonic star within its cocoon of gas and dust as a protostar.

- At the earliest stages of the process, before there even is a protostar, there is just a knot of enhanced density within the cloud. These dense knots, or cloud cores, are the regions where we see the most intense radio light, indicating that gravity has coalesced the gas densely enough there for a new star to form.

- For reference, each of these dense knots is about the size of our solar system, including not only the Sun and planets, but also the larger Oort cloud of comets that swarm around the outskirts of the solar system.

- These very dense knots of gas and dust, buried deep within the dark cloud, are the places where the next stars will form. Indeed, it is this very material that will be gathered up by gravity to fashion these next stars. You could say that there is not yet an embryo, not yet a beating heart, but conception has occurred, and the stellar birth

process is definitively underway here, each one an entire solar system to be.

- Whereas many, if not most, stars are formed in these dense cores of the most massive clouds, some stars are formed within relatively isolated cloudlets, called Bok globules for the astronomer Bart Bok, who spent much of his career studying them. And because they are isolated, these cloudlets offer a unique opportunity to understand the stages of the process of stellar gestation in detail.

- Clouds like the Bok globule B68 are entirely devoid of stars. These clouds, therefore, represent the very beginning stages of the stellar birth process. This is the stellar womb prior to conception. But gravity will continue acting upon the cloud, compressing and shaping it, making it denser still.

- Eventually, this will lead to the central part of the cloud becoming dense and warm enough to become a stellar embryo, glowing with its own heat. When this happens, the protostar makes itself known. Even if not directly visible, you might say that the baby's kicks are definitely felt by the parent cloud. That kicking baby star within the parent cloud has clear consequences that we can see even from the outside.

- Often, a protostar can barely be perceived in visible light, being deep within its parent cloud. However, a protruding jet reveals the kicking baby within. And in infrared light, like the obstetrician's sonogram, we can see the kicking baby directly. The jets of gas that it spews in opposite directions bore through the surrounding cloud, as the baby pushes to free itself and emerge from the womb.

- The jets that newly forming stars shoot help the newborn star to blow away the remnant cloud material from which it formed. Like a baby chick hatching from its egg, the fledgling star pokes holes in its surrounding cocoon. After a million years or so, this is how the baby star will come to be fully revealed.

- It appears likely that all stars go through a tumultuous start. These babies don't coo so much as kick and scream. Call it a bad case of colic. But these colicky babies have fits and bouts, as evidenced by the knots of ejected gas. What causes these colicky fits is indigestion.

- From detailed studies, we now also know that these "burp" episodes correspond directly to the pace at which the baby star ingests material from its parent cloud. In other words, when it eats too much too fast, it spits up.

Accretion and Magnetic Fields

- At this stage of the infant star's development, it is actively feeding from the swirling disk of gas and dust that encircles it. This process, which is called accretion, is how the star continues to feed and bulk itself up.

- Importantly, the accretion process is mediated by the star's magnetic field, which acts to funnel the material in the disk onto the star. Like the Earth's magnetic field that causes compasses to point north, stars are born with magnetic fields that can influence the motions of electrically charged material near the stars. As gravity and friction cause the material in the disk to swirl in toward the star, like water in a tub spiraling in toward the drain, the star's magnetic field directs the incoming material onto the star itself.

- However, that same magnetic field also acts to launch and funnel a portion of that material away from the star, confining and focusing the material into a tight, fast stream. The star's magnetic field is stretched outward by the outflowing material and twisted around by the star's spin so that it takes on a shape like a nozzle on a fire hose. As a result, episodes of enhanced accretion onto the star lead to episodes of enhanced ejection, as bursts of inflowing material are converted into bursts of ejected material.

- The material in the disk of gas and dust swirls in toward and onto the baby star at the center. That material is clumpy, so the baby

star's feeding from that material occurs in little bursts that are then manifested in bursty clumps in the outflowing jets. Fortunately for the star, less gets ejected than is accreted so that the star can and does grow. In any case, it's clear that at those times when the baby feeds most heartily it also burps most powerfully.

- Occasionally, these episodic ejections can be extraordinarily dramatic, giving rise to what is called an FU Orionis event. In this type of event, the protostar suddenly and dramatically brightens by a factor of about 100 and can sustain this new elevated brightness for months or years. The event is named for a star in the Orion constellation that in 1937 suddenly became about 100 times brighter than it was before.

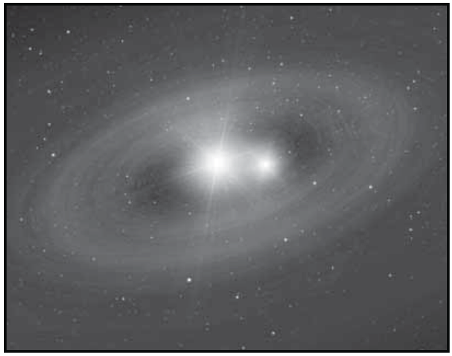
- The current thinking is that these dramatic eruptions are also related to the star's magnetic field. The idea is that, most of the time, the star's magnetic field acts like a dam with a flood gate, holding back the gas and dust in the disk swirling around the star, only letting a small amount through at a time. But every now and then, for reasons that are not clear, the dam breaks, and the gas and dust from the encircling disk come crashing down onto the star, heating it and brightening it temporarily. These dam breaks may also be what drive the knots we see in the jets.

- In fact, those knots of ejected material in the jets very often appear to have a regular spacing, as if the star were ejecting them with a certain cadence. Measurements of the speeds of those knots expelled in the jets, and of the amount of space between them, imply that for most stars, the knots are ejected every 50 years or so. Estimates for the often-dramatic FU Orionis eruptions are similarly every 50 years or so. So it really does appear that those dam breaks are responsible for the knot ejections.

Protoplanetary Disks

- There remains much about this general picture that we don't fully understand; the role of magnetism in the stellar birth process remains one of the frontiers of stellar astrophysics research. In any event, it

is clear that the interrelated processes of accretion and ejection are self-regulated in such a way that the baby star feeds, grows, and—through the feedback of its jets on the cloud from which it feeds—shuts off its own food supply after a few million years.



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Protoplanetary disks can be studied by carefully measuring the amount of light emitted by the disk at different wavelengths.

- So, the baby star has a few million years' worth of time before it is weaned from the bottle. At that point, the star has fully emerged from its cocoon, now an adolescent star ringed with just enough remnant gas and dust from its parent cloud to allow the formation of planets that will orbit it as a solar system.

- These so-called protoplanetary disks can be seen in silhouette against the backdrop of a bright stellar nursery. Their structures can also be studied in detail by carefully measuring the amount of light emitted by the disk at different wavelengths. That's because the gas and dust in the disk that is closer to the star will be warmer than the material farther from the star, and consequently, that closer material will radiate most strongly at bluer wavelengths than the farther-out material.

- Increasingly, astronomers are discovering numerous examples of protoplanetary disks that have certain light wavelengths missing from their emissions. Because the temperature of the material in the protoplanetary disk declines with distance from the central illuminating star, we can map a specific temperature of the material to a specific distance from the star. And because there is a direct relationship between the temperature of a material and its peak

wavelength of emission, we can in turn map a specific wavelength of emission to a specific distance from the star.

- So, the fact that specific wavelengths of emission from the protoplanetary disk are missing indicates that the disk is devoid of gas and dust at specific distances from the star. In other words, something is carving out gaps in the protoplanetary disks. Almost certainly, these are newly formed planets orbiting within the disk and sweeping out large gaps.

Suggested Reading

Astrobiology Magazine, "The Stuff Stars Are Made Of."

European Space Agency, "Born in Beauty."

Questions to Consider

1. What are some of the similarities and differences between the wombs in which baby stars and human babies are born?

2. In what ways are the stellar birth process and the planet-formation process intimately linked?

The Dynamics of Star Formation

Lecture 6

Most stars are not born alone, but in groups. And because they're not born alone, the siblings affect one another—a sibling rivalry starting in the womb. In this lecture, you will learn about the types of stellar siblings that most stars are born with. You will learn about the latest observational evidence, and you will discover that stellar siblings undergo fascinating, and sometimes violent, dynamical interactions that influence everything from their birth weight to their future lives.

Astronomical Terminology

- Astronomers use certain terminology to describe different types of stellar siblings. First, a lone star is simply called a single. Our Sun is, to the best of our knowledge, a single star. Among all stars similar in mass to our Sun, singles are found about 40% of the time. So, while our Sun is not strange, it does represent a bit of a stellar minority.

- The most common arrangement for stars similar in mass to our Sun, about 60% of them, is a binary, or double, star system. You can think of these as twins—sometimes identical, but usually not. In fact, you can think of most binary stars as being fraternal twins; they were born together but otherwise have different characteristics. There are even binary star systems that we can think of as adopted twins; they are together now but were born from different clouds—different parents.

- Although rare, stellar siblings can also come in threesomes, foursomes, or more. There are triplets, what astronomers call trinary star systems, or triples. There are even quaternary systems, which consist of four stars, or quadruplets.

- One of the most extreme examples of multiple siblings is in fact one of the brighter objects in the sky: Castor, which is one of the

two brightest objects that make up the constellation Gemini. Castor is itself six stars—sextuplets.

- The Castor sextuplets have what we call a hierarchical arrangement: The stars are not evenly separated but, rather, involve a nested sequence of tight separations within more distant orbits. Specifically, Castor contains a binary star system orbited by another binary star system, both of which are orbited by an outcast third binary star system.

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The constellation Gemini contains Castor, which is actually six stars.

- There is an important distinction that we need to make when talking about stellar siblings. The only physically meaningful types of siblings are those that are gravitationally bound to one another. Such siblings, by virtue of their mutual gravitational attraction, are most likely to have actually been born together. At the very least, it's clear that the stars are together now, so they likely share a history—past and future.

- This is in opposition to stars that at first glance might appear to be related but, in fact, are not. This can happen when two stars appear very close to one another in the sky but are actually at completely disparate distances from us.

Orbits of Star Systems

- In one type of binary star orbit, two stars orbit one another in simple circular fashion, maintaining a constant separation throughout their orbit. However, stars don't have to orbit in circles. More generally,

their orbits can be ellipses, in which case they make a close, rapid approach and then a slow, distant motion—what we call an eccentric orbit.

- With three stars, the orbits become somewhat more complex. It turns out that many, if not most, configurations of three stars are not dynamically stable for long periods of time. So, in nature we tend to find three stars in a hierarchical arrangement, with two stars close together and the third farther out. In fact, there is a fascinating, stable orbit of three stars called a figure-eight orbit.

- With four stars, while there are in principle more possible arrangements just by virtue of having more stars to arrange, there are in fact only a relatively small number of dynamically stable configurations. Again, the stable configurations have a hierarchical character. In one type of arrangement, two separate binary systems orbit one another. In a multiple hierarchical arrangement, an inner binary pair is orbited by a third star, all of which is orbited by the fourth star.

- In order to remain stable in their orbits for long periods of time, orbits generally have a hierarchical arrangement. When the orbits of multiple stellar siblings are not hierarchically arranged, some dramatic things happen. These dramatics are particularly important within the crowded, dynamical environments of stellar nurseries, the places where stars are born.

- In the relatively simple case of two stars forming out of the same dense core of cloud in a stellar nursery, which essentially represents the idealized gestation of twins within a single womb, there are multiple possibilities for the arrangements of any planets that might form from the material around the stars.

- Planets could form around one or both of the stars individually, because each star maintains a reservoir of gas and dust in a protoplanetary disk around it. Alternatively, or in addition, planets

could form in the material surrounding the entire stellar binary, becoming what are known as circumbinary planets.

- In the same sort of situation, but this time where the two protostars forming within the womb get a bit too close for comfort, the possible arrangements for any planets forming in the system will be different from the binary example.

- In the case of triplet stars, where the tight binary pair has been largely stripped of its reservoir of gas and dust by the close gravitational encounter with the third sibling, planets are unlikely to be able to form around either of those stars. However, the more distant third star will be able to form planets. In addition, there may be enough material surrounding the entire triple system to form circumtriplet planets. In general, if you want to know where the planets are likely to form, just follow the protoplanetary gas and dust in the system.

- In addition, the birth of triplets within a natal cloud of gas and dust involves some amount of jostling of the stars and disruption of the system, both in the sense that protoplanetary material is disrupted and in the sense that one of the three stars is pushed out to a wider orbit compared to the other two siblings.

The Establishment of Hierarchy

- The establishment of hierarchy among stellar siblings when they are born involves a complex, highly dynamical interaction. The need for a system of three or more stars to end up in a strictly hierarchical arrangement may seem counterintuitive. After all, within our own solar system, we have one star orbited by eight planetary bodies spaced out relatively evenly in distance from the Sun.

- But the difference in a stellar triplet system is the much stronger gravitational interaction among these stellar mass bodies. The strength of that interaction is such that the only stable arrangements are hierarchical ones, so these systems naturally

evolve in such a way that they either space themselves out or disrupt themselves trying.

- Indeed, more detailed studies of these interactions involving many simulations and different starting conditions reveal that the resulting stellar triplets tend to have a tightened inner binary pair and a widened outer third star. In other words, over time, two of the triplets move closer together in their orbit, while the third drifts farther and farther away from the inner pair.

- This dynamical process of at once tightening an inner binary pair of stars at the expense of expelling a third sibling turns out to help explain a long-standing mystery about binary stars. It has long been known that the most widely separated binary stars—often referred to as ultrawide binaries—could not have started out as widely separated as we see them.

- Take as an example the separation of Proxima Centauri from Alpha Centauri. Their physical separation is larger than the typical stellar womb—the clouds of gas and dust within which we know stars form. How could stellar twins be farther apart than the womb within which they were born?

- There is a third star in the Proxima Centauri and Alpha Centauri system. Most likely, the three stars actually started out their lives much more closely together, and as the two twins that make up Alpha Centauri came together, feeding from the parent cloud and growing heftier together, Proxima got pushed out, emerging as a little red dwarf star, the runt of the litter.

- Such red dwarf stars are so called because they are the lowest-mass objects that can still perform nuclear fusion in their cores, which is what defines a star. And being such lightweights, as low as one-tenth of the mass of our Sun, they have very cool surfaces, as cool as 3000 degrees Celsius, so they emit primarily long-wavelength red light.

- The most widely separated of the thousands of apparent stellar twins are separated by 3 light-years or more. However, the typical stellar womb is only about one-tenth that size. Research has shown that, in fact, one of the twins was itself a twin. What was thought to be a single star turned out to be a very tight binary pair. So, these systems are actually triplets, consisting of a tight inner binary pair and a distant third sibling that presumably was ejected during the dynamical birth process.

- In an extreme situation in which one of the triplets gets ejected hard and early, what would we see? This early ejection scenario is one of the currently favored theories to explain the existence of so-called brown dwarf stars, which are in fact not stars at all but, rather, stillborn stars—objects whose birth weights were less than the minimum amount of mass that a star needs to ignite as a full-fledged star.

- These objects, choked off during the stellar birth process from their supply of material from the parental cloud of gas and dust, emerge from that process unable to light up as a star, doomed to spend the rest of time slowly fading away, neither star nor planet.

Suggested Reading

NASA Jet Propulsion Laboratory, "Near Earth Object Program."

Wikipedia, "N-Body Simulations."

Questions to Consider

1. What might be some of the reasons that stars are so often birthed as twins, triplets, etc., whereas human twins and triplets are much more rare?

2. In what ways do stellar siblings affect one another and enhance or limit their ability to make solar systems?

Solar Systems in the Making

Lecture 7

In this lecture, you will learn about the part of the stellar life cycle in which stars form their families of planets—their solar systems. You will learn that one of the most successful explanations for our own solar system involves a chaotic, dynamical process in which our planets jockeyed for position, and in so doing, may have been responsible for delivering the Earth its oceans in a hail of comets, the water upon which our very lives now depend.

Protoplanetary Disks around Young Stars

- Protoplanetary disks are the birthplaces of planets; they are solar systems in the making. But these planetary birth sites are fleeting places. Stars like the Sun live a very long time, about 10 billion years. However, these protoplanetary disks disappear quickly after a star is born—typically lasting just a few million years—so planets have to be made very quickly.

- Using infrared measurements of disks around stars in stellar nurseries of differing ages, we can directly trace the evolution of protoplanetary disks. The amount of infrared light emitted by the protoplanetary disks tells us how much gas and dust is there, so by measuring the infrared brightnesses of different star-disk systems, we learn how quickly the disks are consumed by the stars themselves and by the planet-formation process.

- Based on these measurements, we find that when the stars are less than a million years old, nearly 100% of them have protoplanetary disks. But by the time these stellar families are just 5 million years old, only about 10% of the stars still have their disks. So, after an age of about 5 million years, stars simply do not have sufficient material remaining around them to be able to make planets.

- Why is the window of opportunity for planet making so brief? In large part, it is because the process of making planets itself uses up the disk material and, therefore, limits the star's planet-making potential.

- Measurements using the radio light emission of the gas in these disks tell us that young stars with masses like the Sun have just enough material in their disks to make a few times as many planets as those that comprise our solar system. More massive stars generally have somewhat more material, and less massive stars start out with somewhat less.

- These disks actually contain just enough mass within them to make a solar system's worth of planets and some extra. In fact, that bit of extra planet-making potential is probably gobbled up by the star.

- The formation of a planet within a protoplanetary disk of gas and dust can be broken down into 3 stages. First, the forming planet interacts through gravity with the nearby disk material and excites a spiral wave of density propagating through the disk. Next, as the mass of the planet grows from consumption of the disk material immediately around it, an empty gap within the disk at the planet's orbit is cleared out. Finally, the massive planet is able to interact with the nearby disk material strongly enough that it experiences a steady loss of orbital energy, causing it to spiral in closer and closer to the star.

- This spiral of the planet toward the star is referred to as planetary migration, and in some cases, the inward spiral can cause the planet to plummet all the way into the star. But while the idea of planetary migration as an integral part of the planet-formation process has become widely accepted, this idea was very surprising when it was first discovered.

- For most of the history of astronomy, and going all the way back to the philosopher Immanuel Kant in the mid-1700s, our basic ideas for the origin of our solar system were of an orderly process. In the solar nebula hypothesis, the Sun and its system of planets were

thought to have originated from the gradual formation of individual bodies within a rotating nebula of gas.

- Impressively, this basic picture is not so far from the truth as we now understand it, but this picture did not imagine that the planets forming within the solar nebula might have moved or migrated from their original positions to where we see them now. And the Kantian picture certainly did not imagine a process whereby the planets might even be destroyed as they migrate all the way in to the Sun.

- So, in fact, the planetary migration idea is a relatively new one in the history of human understanding, and it represents one of the more surprising and significant advances in our quest to place our planetary home in the broader context of our own solar system and, indeed, in the context of how all other solar systems come to be.

The Planetary Migration Process: The Nice Model

- The planetary migration process serves to further clear out the disk material close in to the star, leading eventually to a cleared-out inner hole in the disk within the planet's orbit.

- The precise location within the protoplanetary disk where a planet starts out is important, because this affects the type of planet it will be. Think about the nature of the planets in our own solar system: Solid rocky planets like the Earth and Mars are close to the Sun while giant gaseous planets like Jupiter and Saturn are farther out. This was recognized early on as an important clue.

- Close to the Sun, where the protoplanetary disk was hot, light elements like hydrogen and helium would have been boiled off of a forming planet, leaving only the heavy rocky and metallic elements to form a small solid planet. Far from the Sun, where the protoplanetary disk was cold, the forming planet could hang on to a very large fluffy atmosphere of light elements.

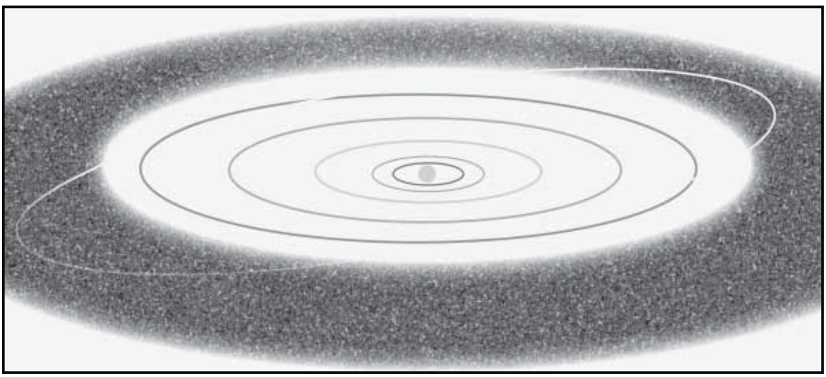
- A successful model for our solar system must be able to account for the 8 major planets, from Mercury to Neptune; the fact that the

inner planets are small and rocky whereas the outer ones are big and gaseous; and the fact that the outskirts of our solar system are littered with comets and other small bodies—the detritus of the planet-formation process.

- That basic model is now referred to as the Nice model, so named for the city in France where a group of astronomers met in 2004 with the goal of developing a comprehensive simulation of the formation of our solar system.

- In the Nice model, it is the gravitational jostling caused by the four massive planets that governs all of the ensuing action. The small rocky planets in the inner part of the solar system are innocent bystanders in a dramatic sequence of events dictated by these titans.

- The giant planets have enough mass to be able to gravitationally perturb the comets and asteroids in the Kuiper belt. Those perturbations send some of these objects inward, into the direct influence of the giant planets. And once the comets come closer to the massive planets, the comets' orbits become extremely unstable due to the strong gravitational slingshot effects caused by their close passages to the planets. Most of these comets and asteroids end up being ejected into interstellar space.



The Kuiper belt consists of hundreds of millions of objects that are supposedly leftovers from the formation of the outer planets.

- But the planets cannot kick the comets out of the Kuiper belt without consequence. Newton's third law states that for every action, there is an equal and opposite reaction. In this case, the reverse effect of kicking the comets and asteroids out of the solar system is to alter the planets' own orbits.

- In particular, the planets' orbits migrate inward or outward, and importantly, orbits that may have started off circular become elongated, what we refer to as eccentric orbits. With eccentric orbits, the giant planets can occasionally interact even more strongly because they can at times come very close together.

- At the critical moment in the Nice model, Jupiter and Saturn hit a gravitational resonance. A resonance is a kind of "sweet spot" in which the eccentricities and proximities of the planets' orbits cause them to orbit the Sun with periods that are an integer multiple of one another. In this case, it is a 2-to-1 orbital resonance, in which Jupiter goes around the Sun twice for every time Saturn goes around once. That resonance means that for a brief time, Jupiter and Saturn interacted very strongly, over and over again, and each time, Saturn's orbit got kicked so that it became more and more eccentric, more elongated.

- At that moment in the solar system's history, Saturn's orbit quickly became sufficiently elongated so that its gravitational influence could begin to affect the planets exterior to it—Uranus and Neptune. In this way, Saturn then forced Uranus and Neptune to begin migrating outward. And in the process of migrating, they actually swapped places.

- That briefly chaotic swapping motion caused Uranus and Neptune to plow through the swarm of comets and asteroids in the Kuiper belt. Their motion into that crowd caused a sudden scattering of huge numbers of comets and asteroids, splattering them all over the place.

- Some of that splash brought a very large number of comets plummeting in toward the Sun and crashing into the planets of the

inner solar system, including the Earth. The geologic record of the Earth and our Moon clearly shows that an event referred to as the late heavy bombardment occurred around the time when the solar system was about 600 million years old.

- The late heavy bombardment was a brief event in which a large number of solid bodies suddenly impacted the Earth and Moon. Sure enough, the Nice model has the Neptune-Uranus swapping event occurring right around the time of the late heavy bombardment.

- An intriguing additional consequence of this scenario is its potential to explain the abundance of liquid water on Earth. Comets are often referred to colloquially as dirty snowballs—a mixture of solid material, including rocks and metals, together with ices of various compounds, including frozen water. Calculations that take into account the number of comets and their content suggest that, indeed, the Earth's oceans could have been supplied with much of their current water content by a bombardment of comets raining down from the sky.

- There is some debate in the scientific community over whether the Nice model's prediction of Neptune and Uranus swapping is correct. However, this aspect of the model is not necessarily essential to its overall success in explaining many of the features of our present-day solar system. By changing the starting conditions of the solar system's planets slightly, much of the same behavior occurs, but without the two planets swapping.

- Of course, as with any scientific model, the Nice model has its limitations. While the model seems to successfully capture many of the essential ingredients in the evolution of our solar system—with or without Neptune and Uranus swapping places—it does not attempt to explain how the planets came to be in their starting positions, only what happened to them afterward.

- Indeed, it remains an outstanding question how the planets in our and other solar systems manage to avoid falling in to their suns. The

issue is that the planet-migration process within the protoplanetary disk is so effective at spiraling the newborn planets toward the star that in many calculations, the planets just keep on spiraling in until there are no planets left. The parent star in effect cannibalizes its own planets before they even really get a chance to jostle one another, as in the Nice model.

- So, many astronomers believe that the process of planet formation is sufficiently prolific that the parent stars can afford to cannibalize many of the planets, and then, once the protoplanetary disk is used up and the planet-migration process is halted, there are sufficient planets remaining to populate the solar system thereafter.

- The protoplanetary disks from which the planets form typically contain enough material for a few times as many planets as what we currently see in our solar system. Those extra planets almost certainly do get made, but we don't see them now because they ended up devoured by the Sun.

Suggested Reading

Brandner and Klahr, *Planet Formation*.

Sky & Telescope Magazine, "Video: Evolution of the Solar System."

Questions to Consider

1. How does the idea of conservation of angular momentum help explain why stars form flattened disks of gas and dust from which their planets form? Why is it a flattened disk as opposed to, for example, a bubble of gas and dust around the star?

2. How does the idea of "jockeying" planets compare to the traditional view of how our solar system came to be, and how does this dynamic view of planetary system formation help us understand the types of solar systems now being discovered around other stars?

Telescopes—Our Eyes on the Stars

Lecture 8

Everything we know about the stars has been learned through the information carried by the light that the stars emit. But for us to make use of that light, to be able to actually learn something about the stars from it, it must also be detected and recorded. In this lecture, you will learn about the instruments astronomers use to measure starlight. Merely to detect light is not so difficult, but to record it with sensitivity and accuracy is, in fact, a remarkable feat.

Types of Telescopes

- Our eyes, in their form and function, are small telescopes with built-in light detectors. Light that reaches your eye is brought to a focus by the lens—that's the telescope part—and the focal point is the retina, which has light-sensitive chemicals to absorb the light—that's the detector part. In one way or another, that's what every astronomical telescope does: It uses an optical element to focus the incoming light and a light-sensitive detector to absorb and record the light.

- The ability of the human brain to store visual information in the form of memory is, of course, absolutely wonderful. But as a means for making accurate measurement, the human visual system leaves much to be desired. First, most of the information that we see is recorded only temporarily and then lost forever. Second, even if it could be recorded forever, there are limitations to what our eyes can do as telescopes. Our eyes are only sensitive to a small portion of the entire electromagnetic spectrum, what we call the visible part.

- In addition, the response of our retinas to the amount of light received is what we call nonlinear. That means that there is not a simple linear relationship between the apparent relative brightness of different objects and their *true* relative brightness.

- In fact, our eyes' response to light is logarithmic. A star that appears to our eyes to be 5 times as bright as another is in fact 100 times brighter. This is a helpful property for our needs in everyday life, because it means that we can handle looking at things that have a very large range of relative brightness, but for accurately measuring quantities of light, a linear response is much more desirable.

- The digital detectors attached to most telescopes have this property: They respond in a linear way to light, so a star that is twice as bright as another is faithfully recorded as being twice as bright. In addition, our eyes are relatively small—in particular, the lenses of our eyes are small—and so are only sensitive to the brightest stars. To see fainter stars requires a larger light-gathering device—in other words, a larger telescope.

- There are two basic types of telescopes that astronomers use to observe stars in visible light, and they differ only in the nature of the optical element that focuses the incoming light. The first type is called a refracting telescope, because it uses lenses to refract, or bend, the incoming light and thereby bring the light to a focus. This is the type of telescope that most people associate with astronomy, and for much of history, this is the type of telescope that astronomers used.

- The second main type of telescope is called a reflecting telescope, which is so named because, rather than using a lens to bend the light to a focus, it uses mirrors to reflect the light to a focus. Today, all major astronomical telescopes are of the reflecting variety.

- A reflecting telescope can be built with a much larger mirror than it is possible to fabricate a lens. A lens is a solid piece of glass, so a larger lens is necessarily heavier—much heavier. In contrast, a mirror can be made large but thin.

- Another advantage of a reflecting telescope is that, in contrast to the long tube of a refracting telescope, a reflecting telescope can be built relatively compact. That is because the long focus can be

accommodated with multiple reflections off of a series of mirrors, in essence folding the light beam.

Properties of Telescopes

- The two most important properties of telescopes are light-gathering power and angular resolution. Light-gathering power refers simply to the ability of a telescope to collect light. The more the better, because the more light that a telescope can capture from a star, the fainter the star the telescope can see and the more sensitively it can measure the properties of that light.

- The single most important property of a telescope that determines its light-gathering power is the area of the primary optical element. In other words, the bigger the lens or mirror, the better. The bigger the primary mirror of the telescope, the more photons that can be gathered quickly. And because the area of the mirror is the square of the diameter, by making the mirror twice the diameter, you get four times the area—four times the light-gathering power—and you can see a star that is four times fainter or measure the same star four times more sensitively.

- The second important property of any telescope is its angular resolution, which refers to the crispness with which a telescope can focus the incoming light. The better the angular resolution, the crisper the focus that can be achieved, and this allows ever-finer details in the stellar images to be discerned.

- The size of the telescope's primary mirror determines its angular resolution. A small telescope has poor angular resolution, so a star appears fuzzier. The formula that describes the angular resolution of a telescope is as follows: $\theta = \lambda/D$.

- This formula says that the best focus a telescope can achieve, the smallest angle a telescope can discern, the finest detail that the telescope can make out—call that angle θ—is the wavelength of light divided by the diameter of the telescope's primary mirror. So, for a given wavelength of light, λ, this formula says that a larger-

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The Mauna Kea Observatory, an astronomical observatory in Hawaii, lies on top of the peak of the dormant volcano named Mauna Kea.

diameter mirror will achieve a smaller angle of focus. That is, with a finer focus, finer details can be discerned.

- Both of the most important properties of a telescope—light gathering power and angular resolution—depend directly on the size of the telescope's primary mirror.

Digital Detectors and Filters

- The basic component of any modern astronomical detector—the "retina"—is a digital detector similar to what you find in your digital camera or phone. That detector is essentially just a chip of silicon that is subdivided into tiny squares, called pixels.

- Each pixel is a tiny photoreceptor that responds to incoming light by what is known as the photoelectric effect, which states that when a material absorbs the energy of a photon of light, that energy causes an electron within the material to be freed, and that electron

then joins other electrons as part of an electric current that can be measured.

- Each absorbed photon therefore liberates one electron, so by measuring the strength of the electric current produced in the material, we can measure accurately and linearly the number of photons that struck the detector. With many pixels in the detector linked together, each one acting as a photon counter, we can build up an image, each pixel measuring a tiny part of the overall image.

- Measuring the color of a star is one of the basic ways that we can determine its physical characteristics, and the photoelectric effect by which the digital detector measures incoming photons doesn't care about the wavelength of the incoming photons. In essence, the digital detector only tells us whether light was detected, and how much, but not its color.

- To get color information, astronomers use filters. A given filter lets through light of only a particular wavelength—for example, red, or blue, or green. By combining images taken through discrete filters, we are then able to create images that convey the true colors of the stars, and we can use the color measurements to determine things like the temperatures of the stars.

- Much of the true power of light to convey physical information about the stars comes not from mere pictures, but from the spectrum of light. Spreading the light we receive into its constituent rainbow and then dissecting those wavelengths is ultimately how we learn the star's temperature, chemical makeup, motion, and many other properties.

- To spread the light gathered by a telescope into a spectrum, the light has to be focused onto a light dispersing element, which is in general one of two different types of optical devices: a prism or a grating.

Beyond Visible and Radio Light

- Visible light is one of the only types of light that can penetrate through the Earth's atmosphere and reach telescopes on the ground. The Earth's atmosphere acts like a screen that absorbs almost all wavelengths of light. From the ground, the only wavelengths of light that can be seen coming from the outside are visible light and radio light.

- A small portion of the infrared part of the spectrum, called the near-infrared part, can be seen from high mountaintops or from instruments flown at very high altitude. At these heights, the atmosphere above is thinner, so enough of the incoming light is able to penetrate and be detected. Even for visible light, placing our telescopes on high places is an advantage.

- Beyond visible and radio light, it's necessary to put telescopes above the filtering of the Earth's atmosphere. All of our ability to study the stars at ultraviolet, X-ray, and gamma-ray wavelengths—and most of our ability to study the stars in infrared light—comes from space-borne telescopes.

- Because these telescopes gather starlight from above the Earth's atmosphere, they additionally are able to obtain images with a crispness that is normally not possible from the ground. Putting telescopes in space is an extremely expensive thing to do, but major technological efforts are underway to develop new ground-based telescopes, operating at visible and radio wavelengths, that can achieve the same degree of precision focus—the same crispness—as is currently possible only from space.

- There are two methods currently being developed that show great promise: adaptive optics and interferometry. With adaptive optics, the telescope's primary mirror is connected to a large set of precise motorized controls that can push and pull on pressure points beneath the mirror's surface, so as to intentionally deform the mirror.

- With interferometry, multiple telescopes are used in unison so as to mimic the performance of a single monolithic telescope as big as the smaller telescopes are apart. An interferometer doesn't have the same light-gathering power as a telescope, so it's not as sensitive to light from fainter stars, but in cases where angular resolution is more important than sensitivity, interferometers are the way to go. And no other approach—not even a telescope in space—can beat the fantastic fineness of detail that can be achieved.

Suggested Reading

Giant Magellan Telescope Observatory, "Giant Magellan Telescope (GMT)."

Large Synoptic Survey Telescope, "Large Synoptic Survey Telescope (LSST)."

Lowell Observatory, "Navy Precision Optical Interferometer."

Questions to Consider

1. In what ways do the basic tools of the astronomer—telescopes and cameras and spectrographs—compare to or differ from those used by scientists in other disciplines?

2. How have technical advances in astronomical instrumentation enhanced our everyday lives?

Mass—The DNA of Stars

Lecture 9

In this lecture, you will learn how astronomers use the information encoded in the light from binary star systems to measure the properties of the stars, to weigh the stars, and to thereby establish that mass is the DNA of the stars—determining all of its other physical properties. In order to fully appreciate how astronomers arrived at this understanding of mass as the stellar DNA, you will embark on a train of logic building on several topics that were presented in previous lectures.

Stellar Mass

- The most important property of a star is its mass, which determines all of its other characteristics. Indeed, a star's mass determines everything about its life—how long it will live, for example, and even the manner in which it will die. In a sense, mass is a star's DNA, specifying all of its physical characteristics.

- But while our own DNA governs certain things about us physically and otherwise predisposes us to certain personality characteristics and behaviors, our ultimate life paths are also influenced by many factors that have nothing to do with our DNA. But for a star, mass is totally deterministic. We would not know this fact if not for the existence of binary stars—systems in which two stars orbit one another.

- The only way to weigh anything is to measure its gravitational effect on something else, or vice versa. For example, we know the Sun's mass because we can measure its gravitational influence over the planets that orbit it, such as the Earth. We can measure how far the Earth is from the Sun in its orbit, and we can measure how long the Earth takes to orbit the Sun. These are fundamentally measures of the Sun's gravitational influence and, therefore, are measures of the Sun's mass.

- When we want to study stars other than the Sun, we need a tracer that we can easily detect and measure in order to determine the strength of that star's gravitational influence, or mass. The most convenient thing is another star, bright enough to see, itself massive enough to exert its own gravitational influence that we can measure. By studying binary stars, we not only have the requirement of an orbiting body to reveal the strength of the other star's gravity, but we are also able to measure the characteristics of two stars at once.

- There are three main types of binary star systems: visual binaries, spectroscopic binaries, and eclipsing binaries. Visual binaries are pairs of stars where we can actually see the two stars separately. Because of the great distances that most stars are from us, the fact that we can see the two stars as separate points of light means that in reality, they must be separated by a very large physical distance.

- Consequently, the orbital periods of most visual binary star systems are extremely long, too long in most cases for us to be able to see the orbital motion. However, in some cases, the stars are close enough to us that we can actually see the orbital motion of the two stars directly.

- Although visual binaries for which we can directly observe the orbit are relatively rare, they are wonderful systems to study because of the relative simplicity of making the necessary measurements. Just a series of photographs over time allows us to measure the two key properties of the orbit that we'll need: the time it takes for the stars to orbit, what we call the orbital period; and the size of the orbit, or the physical separation of the two stars.

- The second type of binary star system is a spectroscopic binary. These get their name from the fact that, visually, they appear as a single star, a single point of light. However, when we examine their spectrum, the fact that it is actually two stars becomes revealed.

- An advantage of spectroscopic binary stars is that, because they are so close together that in images they appear as a single star, we learn that they orbit one another quickly. Most spectroscopic binary star systems have orbital periods of less than a year, and many have periods of just days. So, in a short period of time, we can collect spectra at different points in the stars' orbit and measure from the spectra the information that we need to put into Newton's law to determine the stars' masses.

- Finally, there is a third type of binary system, which is arguably the most valuable of all: eclipsing binary stars. These are usually spectroscopic binary stars also, but they have a rare but special property. From our perspective on Earth, their orbit happens to be oriented such that the two stars periodically pass in front of one another, temporarily blocking—or eclipsing—the light of the other star. When this happens, the total light that we receive from the two stars together becomes temporarily diminished, and the pattern repeats.

- Eclipsing binary stars are extremely valuable and important. That's because not only can we analyze their spectra in the same way as for other spectroscopic binary stars, but we also have the eclipses, which tell us an additional crucial piece of information: the diameters of the stars.

- With knowledge of how fast the stars are orbiting one another from the Doppler measurements of the spectra, together with a measurement of how long the eclipses last, we can calculate physically how large the stars must be. This is one of the only ways that we have of directly measuring the sizes of stars.

The Hertzsprung–Russell Diagram

- Almost 100 years ago, two astronomers, Ejnar Hertzsprung and Henry Russell, used a set of hundreds of stars for which some measurements had recently become available. Importantly, this included stars that were nearby enough to have all of the basic

properties measured by which their masses and diameters could be determined.

- First, their distances could be measured via parallax. Second, their temperatures could be measured from their colors and spectra. Third, their luminosities could be measured from their apparent brightnesses together with the parallax distances. Finally, the stars' masses could be determined from binary-star measurements and diameters determined from the eclipsing binary stars in the sample.

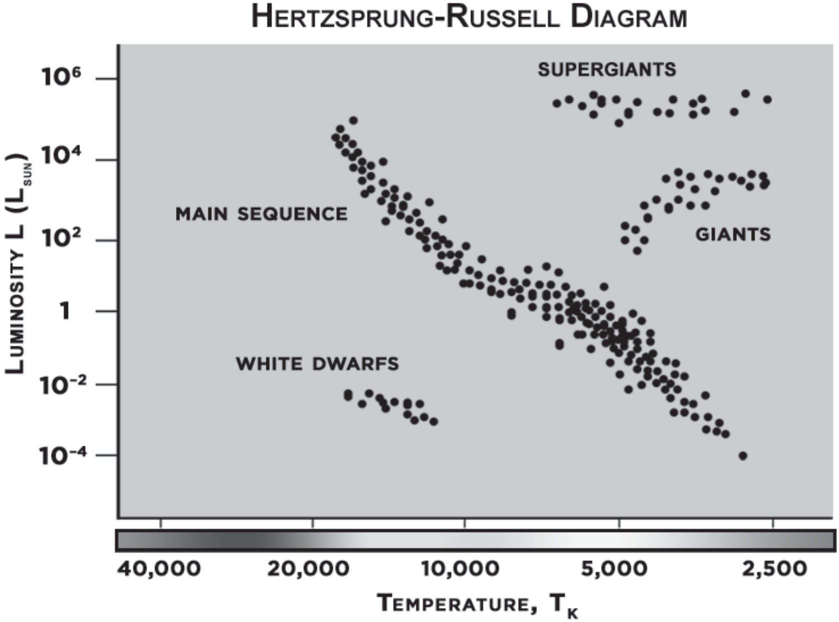
- Hertzsprung and Russell made a diagram from these measurements that we still use today as one of the most fundamental astrophysical tools for understanding the properties of stars. It's called the Hertzsprung–Russell diagram, or H–R diagram, which is simply a graph of luminosity on the vertical axis and temperature on the horizontal axis.

- For historical reasons, the diagram is always represented with luminosity increasing on the vertical axis but with temperature decreasing on the horizontal axis. Stars farther up are more luminous, but stars farther to the right are cooler. Also, for reference, the Sun has a temperature of about 6000 degrees Kelvin and a luminosity of 1 solar luminosity.

- Temperature and luminosity are two of the fundamental properties of stars that we can directly measure for most stars. Luminosity we can measure from a star's apparent brightness and its distance. Temperature we can measure from a star's color, using Wien's law.

- There is also a second way of measuring a star's temperature, using details of its spectrum. A star's spectral type can be denoted by one of the following letters: O B A F G K M. Each letter represents stars whose spectra have a certain appearance and, therefore, a certain range of temperatures.

- In that order, O B A F G K M, the number of chemical absorption fingerprints increases. And in that order, there is a temperature



sequence, with the O stars being the hottest and the M stars the coolest. On the H–R diagram, we can represent the stars' temperatures on the horizontal axis either as physical temperature in Kelvins or in terms of the stars' spectral types.

- Graphing the stars that Hertzsprung and Russell knew about, essentially a random assortment of stars having nothing in common other than being relatively close to us, we find that the stars are not scattered randomly in the graph. Instead, the stars form a narrow diagonal band across the diagram. About 90% of all stars reside on this diagonal swath, which is now referred to as the stellar main sequence.

- At the most basic level, the main sequence tells us that stars are made in such a way that they have only certain particular combinations of temperatures and luminosities. The hottest, bluest

stars—the O-type stars—are extremely luminous, and the coolest, reddest stars—the M-type stars—are extremely dim.

- Once we know the main sequence, we can infer the luminosity of any star just by measuring its temperature. Temperature is a relatively straightforward property to determine, because we need only measure a star's color or its spectrum. Luminosity is more difficult. By "luminosity" we mean the intrinsic energy output of the star, not simply how bright it appears to us in the sky. A star can appear bright because it's simply nearby, not necessarily because it is intrinsically luminous. So, to determine a star's true luminosity, we also need to know the star's distance, such as measured using the parallax triangulation method.

- But the real power of the main sequence is what it reveals about the underlying stellar DNA. When we add the information that we have regarding the stars' masses, as measured from the binary stars, we find a clear and unmistakable correlation: The hottest, most luminous stars are also the most massive, while the coolest, least luminous stars are also the least massive.

- In other words, the main sequence of the H–R diagram reveals that what fundamentally drives the physical properties of the stars is one thing: mass. And it's a prescriptive relationship. A star born with a mass equal to that of our Sun always has the temperature of our Sun and its same luminosity.

- A few percent of stars appear at the upper right of the diagram, and a few percent appear at the lower left. A star at the upper right in the H–R diagram has a very cool temperature but an extremely large luminosity. We can infer that those stars are physically very large, and we call them giants and supergiants. These are stars at an elderly stage of life, approaching their deaths.

- At the lower left, the opposite reasoning applies. These stars are hotter than the Sun yet extremely dim. That's because they have tiny sizes. We call these white dwarfs. These are not stars at all, or

at least not living stars. They are the corpses of stars like our Sun that have ended their lives and are now just fading embers made of nearly pure carbon—diamonds in the sky.

- About 90% of stars are on the main sequence, and the rest are giants, supergiants, and white dwarfs. This tells us that stars spend the vast majority of their lifetimes—about 90%—as members of the main sequence, and then a small portion of their lives, the end of their lives, as giants and white dwarfs.

- In other words, stars spend most of their lives in a happy, stable configuration with a particular temperature and luminosity, and then end their lives relatively fast. When the end comes for a star, it evidently comes quickly. And all of this is dictated by the star's mass.

- When we perform a census of the stars by their masses, we find that there are relatively few very massive stars, more mid-weight stars, and many runts. Mass is a star's DNA, and where the star gets that DNA is the stellar birth process, which establishes the star's birth weight. The stellar birth process does not birth stars of all masses equally. Rather, the process of gravitational collapse and the subsequent feeding of the baby stars in their cocoons of gas and dust prefers by an enormously large margin to make lots of little stars and only rarely makes a massive star.

Suggested Reading

Kallrath and Milone, *Eclipsing Binary Stars*.

University of Nebraska at Lincoln, "Eclipsing Binaries Simulator."

Questions to Consider

1. In what ways are binary star systems essential tools for our general understanding of the physical properties of all stars?

2. If the pattern of stellar masses involves a power law, whereby many more lightweight stars are formed for every massive star, do we expect that there will be an even larger number of brown dwarfs, stillborn stars with masses less than the minimum mass required for a star? If not, how does nature know during the stellar birth process to principally make only objects that will eventually light up as full-fledged stars?

Eclipses of Stars—Truth in the Shadows

Lecture 10

In this lecture, you will learn how eclipses can have tremendous applications to many aspects of the stars and the systems of planetary worlds that orbit them. Eclipses help us directly measure the properties of stars from afar and are, therefore, invaluable tools for telling us what stars are like, physically, at different stages of their life cycle—from eclipses of our own Sun by our Moon, to eclipses of more distant stars by our Moon, to the shadows cast by tiny worlds orbiting other suns and whose properties we can measure by virtue of the light we don't see.

Solar Eclipses

- Solar eclipses by the Moon have been observed by people for as long as humans have existed. A total eclipse of the Sun by the Moon occurs somewhere on the Earth every 18 months or so. But any particular location will be able to see a total eclipse only once every few hundred years. Even so, over the course of human history, this is frequent enough that many, many eclipses have been observed, documented, and discussed over the centuries.

- Solar eclipses are astounding cosmic coincidences. First, the Moon orbits the Earth in very nearly the same plane as the Earth orbits the Sun. This allows the Moon to pass directly between the Earth and the Sun. But it's not perfectly aligned—it's tipped by a few degrees—so the Moon's path does not intersect the line between the Earth and Sun every time around. If it did, solar eclipses would occur every month, and they probably wouldn't be regarded as any more special than the new Moon once a month.

- The other coincidence is that the relative sizes of the Sun and Moon are almost exactly the same as their relative distances from the Earth. The Moon is a lot smaller than the Sun, but it's also a lot closer. And it's closer by just the right amount so that the Moon appears to cover the same angle in the sky as does the Sun. So,

when the Moon's orbit brings it directly between the Earth and Sun, it can almost exactly cover the Sun entirely. That is what we call a total solar eclipse.

A solar eclipse happens when the Moon comes between the Sun and Earth, from the perspective of a person on Earth.

- A total eclipse can only be seen from a relatively small region on the surface of the Earth. That's because the shadow cast by the Moon on the Earth is quite small, owing to the Moon's small size compared to the Earth. Pictures taken from space of the Moon's shadow on the Earth show this beautifully. And because the Earth is 70% ocean, most total eclipses occur over the ocean and must be viewed from ships, which adds to the rarity of their sightings.

- Not all eclipses of the Sun by the Moon are total. There are also partial eclipses, when the Moon's path brings it close to but not perfectly in a line between the Earth and Sun. And there are also annular eclipses. These beautiful events occur when the Moon passes directly in front of the Sun as in a total eclipse, but the size of the Moon appears to be just a bit smaller than the Sun.

- This happens because the Moon's orbit around the Earth is not a perfect circle—it is slightly elongated, or elliptical—so sometimes the Moon is a little farther away from the Earth than at other times so that it does not fully block the full face of the Sun. It leaves a ring of sunlight showing, an annulus.

- With total eclipses, the fortuitous coincidence of the alignment and the relative sizes of the Moon and Sun means that we can observe

phenomena on the Sun's surface that we would not be able to observe otherwise. As the totality of an eclipse occurs, we see a phenomenon known as Baily's beads, which are the result of bright sunlight reaching our eyes through craters and valleys on the Moon. Finally, the red glow of the Sun's thin, hot chromosphere becomes visible as a ring around the Moon's silhouette, and then the total eclipse reveals the faint, shimmering glow of the Sun's superhot corona.

- It was through eclipses of our Sun that these hot layers extending above the Sun's surface first became known and, by extension, how astronomers came to suspect that other stars might exhibit these phenomena also.

- In addition, during a total solar eclipse, phenomena such as prominences and flares on the Sun's surface can be observed directly. Although these energetic magnetic events are now routinely seen with ultraviolet and X-ray telescopes, normally these are not visible to the eye because of the intense glare of the Sun's photosphere. But during an eclipse, they can be seen directly, and before the development of modern telescope technologies, these prominences and flares provided some of the first clues about the Sun as a magnet.

- Eclipses can and do happen also with other stars besides our own Sun. The most common version of this is when two stars orbiting one another, a binary star system, have their orbit viewed edge on from the perspective of Earth. When that happens, the stars periodically eclipse one another, and we temporarily receive less total light from the system because the light of one of the stars is blocked.

- One of the most important uses of such eclipsing binary star systems is that they allow us to directly measure the diameters of stars by using the following formula: $d = rt$, or distance equals rate times time. With stellar eclipses, we can determine the speed of the stars' motions from the Doppler shift of their light spectra. Then, we can time how long the dimming of the total light from the system lasts, as one star passes directly in front of and across the other. The speed of

the stars' motion, times the duration of that crossing, tells us directly the distance across the star that was traveled—its diameter.

Lunar Occultation

- Amazingly, there are a few bright stars in the sky that can be eclipsed by our Moon. For technical reasons, this is referred to as lunar occultation. Lunar occultations are another tool for measuring the diameters of distant stars. That's because the edge of the Moon is so sharp that when it passes in front of a distant light source, we can actually measure the brief but finite amount of time that it takes the Moon's edge to traverse that distant light source.

- If the light source were extremely distant, or very small, then it would effectively be a point of light, so the Moon's edge would traverse it instantaneously. The light from the star would just instantly wink out. However, if the star has some measurable dimension, then the Moon's edge will take a measurable amount of time to traverse it.

Coronagraphs

- Nature is not always kind enough to provide an ideal object for eclipsing something that we might wish to eclipse. In those cases, we can create our own eclipses using a device known as a coronagraph to act like an eclipsing body.

- One of the most common uses of coronagraphs is to observe and measure coronal mass ejections from our Sun. Coronal mass ejections are energetic, magnetic blasts that fling material from the Sun's surface out into interplanetary space. But like other solar phenomena that we can only see when the Sun's glare doesn't drown them out, these coronal mass ejections are very faint because they are diffuse.

- However, by placing a metal disc in a satellite and holding it out in front of the satellite's camera at just the right distance, the face of the Sun can be obscured, and the wispy coronal mass ejections can be seen faintly emerging from the edges of the coronagraph.

- With these types of coronagraphic studies of solar coronal mass ejections, we can directly measure the amount of material being ejected from the Sun, as well as its direction and speed. This helps astronomers improve predictions of bad space weather that might cause disruptions in our power grids or knock out communications satellites. This same type of coronagraphic technique can also be used to image faint material or objects around other stars.

Applications of Eclipses

- One of the most important uses of eclipses today for the study of planets around other stars is the transit method, which has revolutionized our ability to discover solar systems by the hundreds and provides astronomers with a powerful way to understand the nature of these other worlds, to ascertain their characteristics, and to use them as fine probes of the surfaces of their host stars.

- When a planet orbiting its star passes directly in line between its star and our sightline, the planet blocks a tiny portion of the star as seen by us. We can't see the star's surface per se; the star just appears as a point of light. Nonetheless, the small blocking of a bit of the star by the planet casts a tiny shadow on us from that enormous distance. And, as a result, we briefly see a tiny bit less light from the star. The star is being eclipsed in a very small way by its planet.

- Mathematically, the fractional amount by which the light of the star is briefly dimmed during the transit of the planet is the same as the fraction of the planet's size to the star's size. More precisely, it is the ratio of the planet's apparent area to the star's apparent area.

- Simply by measuring the fractional amount of light dimming during a planetary transit, we have a measurement of the planet's physical size in relation to the star's physical size. However, we cannot know the actual physical size of a transiting planet without first knowing the size of the star that it eclipses.

- This is where eclipsing binary star systems come to be so valuable and important. By learning what the diameters of stars of different temperatures are from the study of eclipsing binary star systems, we can confidently infer the diameters of other stars from their temperatures.

- When studying these transiting planets, astronomers can use a technique known as transmission spectroscopy to make direct measurements of the chemical compositions of their atmospheres. The measurements reveal that some of those planets appear to have strong temperature inversions in which the outer layers of the planet are actually hotter than the inner layers, whereas others do not. This phenomenon is not yet well understood.

- Another application of eclipses is microlensing, which refers to the brief but dramatic brightening of a star when another star passes directly between it and us, causing the gravitational bending of the more distant star's light to be focused toward us. If the foreground star, the one doing the focusing of the starlight, should possess a planet, the brightening signal will exhibit a bump.

- It is as though the foreground object is a lens, and the planet orbiting the lensing star is a blemish on the lens. This is an amazing application of Einstein's theory of relativity, which was originally vetted using the bending of starlight by the Sun, to the eclipse of distant stars by more nearby ones. And because the microlensing brightening is so dramatic, it can be used to detect planets among stars at great distances.

Suggested Reading

Mobberley, *Total Solar Eclipses and How to Observe Them*.

Steel and Davies, *Eclipse*.

Questions to Consider

1. What types of information about the Sun are possible to gain only during solar eclipses? Would we be able to ascertain the same information, or as accurate information, if not for the happy accident of the Moon's angular size being the same as the Sun's?

2. What are some of the challenges involved in detecting planets around other stars through their eclipses? What types of stars might be best suited for detecting such planetary transits? What are the pros and cons of searching for planetary transits around different types of stars or around stars at different stages of their lives?

Stellar Families

Lecture 11

In this lecture, you will learn about the different types of star clusters—the stellar families into which most stars are born and spend the early stages of their lives. You will learn that these stellar families come in two basic varieties, representing what might be considered modern versus old-fashioned families. Like human families, most modern stellar families disperse over time, in contrast to the old-fashioned stellar families, which were and remain extremely tight knit.

Types of Star Clusters

- There are two main types of star clusters: open clusters and globular clusters. Globular clusters are highly organized, dense, shapely clusters with a spherical or globular appearance, like a swarm of bees around a hive. Open clusters are looser, generally somewhat less ordered in their structure. They appear more "open" as opposed to the dense, compact appearance of the globulars.

- The two types of clusters represent two very different kinds of entities—in terms of their compositions, where they are found, and the evolutionary stage of our galaxy when they were formed. The globular clusters are ancient, old-fashioned families. The open clusters are younger, more modern families.

- The stars forming in the giant clouds of gas and dust of stellar nurseries tend to have a certain organization. In particular, the most massive stars are generally found at the centers of these nurseries, surrounded by a larger collection of less massive stars. In addition, when the stars are still in their nurseries, they are embedded in the gas and dust from which they formed.

Open Clusters

- Looking at the youngest open clusters that we know, we can see the vestiges of these beginnings. We can see remnants of the gas and

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The two general types of star clusters are open clusters and globular clusters.

dust from which the stars were formed, wisps still floating within the cluster. Think of these wisps as the placental material left over from the stellar birth process.

- Another aspect of the stars in the youngest open clusters, representing stellar families soon after birth, is that we see in them the full span of stellar types—from the most massive to the least massive and everything in between.

- When we measure the masses of all of the hundreds of stars in a young open cluster, we see that the pattern of stellar masses is created in the birth process, and the stars carry that pattern forward through the rest of their lives.

- As we look at increasingly older open clusters, we find three important characteristics that reveal what happens to the stars in these families over time. First, we find that the older clusters have

a looser distribution with more space on average between the stars. Second, we find that the older clusters tend to have fewer members. Third, the pattern of stellar masses changes, with fewer and fewer massive stars.

Globular Clusters

- Globular clusters are much more extended stellar families. Whereas typical open clusters have hundreds to perhaps a couple thousand members, globular clusters have tens of thousands to a million members. As a result of their sheer heft, they are very tight knit, and they are much better able to remain bound together for a very long time—at least for as long as the galaxy and the universe are old.

- In fact, we only know of globular clusters that are extremely old, as old as our galaxy. These relic clusters tell us about the conditions of our galaxy when it first formed. In fact, by studying the chemical makeups of these stars, we find some of the least chemically endowed stars in our galaxy. In other words, these stars are made up almost purely of hydrogen and helium, in the proportions that hydrogen and helium were produced in the big bang.

- These stars did not benefit from the production of heavier elements by previous generations of stars. These stars were formed from pristine material from the birth of our universe. But, interestingly, there are trace amounts of heavy elements in these otherwise pristine ancient stars.

- This harkens back to a time when our galaxy was taking shape from an immense protogalactic cloud of gas produced in the big bang. That protogalactic cloud had not taken the flattened pancake shape that we have now. Instead, the galaxy initially had a more amorphous shape, so the very first generations of stars to form would have formed in clusters distributed about the center of the galaxy and bearing that amorphous distribution.

- As the galaxy evolved into the spiral disk galaxy that we have now, the globular clusters retained their distribution, continuing to

swarm about the center of the galaxy. The motions of these globular clusters keep them far from the disk of the galaxy, where they might be disturbed by other stars or clouds of gas and dust. Consequently, these ancient stellar families have remained tight knit from the very beginning.

- But that's not to say that they have not changed since their formation over 10 billion years ago. In fact, they have changed steadily over time. As these stellar families have aged, individual stars have died, with the most massive stars dying first and then successively lower-mass stars dying off. As a result, only the lowest-mass stars remain in these families.

- In a typical globular cluster, all of the remaining stars have masses similar to our Sun or less. Interestingly, though, in many globular clusters, we see some stars that appear to be too massive to still be alive. These are called blue straggler stars.

Dynamical Interactions

- The stars in globular clusters have undergone dynamical interactions over the eons, and these interactions have shaped the clusters in important ways. Stars born as triplets undergo a dance in which two of the siblings are brought closer together, and a third star is pushed out into a distant orbit. A similar process occurs within the globular cluster as a whole.

- In this process, many individual gravitational flybys and kicks among the stars lead to a population of the stars coming closer together at the core of the cluster, while another group is pushed out into wider orbits about the cluster. So, the cluster ends up with what we call a core-halo structure, dense at the center and surrounded by a somewhat looser swarm of stars that have been kicked to the outer limits of the cluster.

- These dynamical interactions also produce other important effects for globular clusters. Some of the stellar corpses of stars that have already died—the white dwarfs—will be members of binary star

systems. And when those binary systems come closer and closer together as a result of the dynamical interactions in the cluster, mass from the stellar sibling of the white dwarf can spill onto the white dwarf and cause it to explode as a supernova. That supernova explosion can flash forge heavy elements, which then can lightly pollute the otherwise pristine stars in the cluster.

- Another consequence of these dynamical interactions in the cluster is that, occasionally, two stars can be brought close enough together to merge. When that happens, the resulting star will be more massive, having the sum of the two original stars' masses. So, the cluster can, for a short time, appear to have a few massive stars that should have died long ago—as if they had been resuscitated or reborn—which explains those blue stragglers.

- These types of dynamical interactions can take place within open clusters as well, and although the consequences are generally somewhat less dramatic, the byproducts are nonetheless very interesting. When an open cluster is undergoing the slow process of disintegrating, its members slowly drifting apart, there can be occasional flybys of stars that come close to stars within the cluster. As a result, the stars receive a strong gravitational kick that ejects them from the cluster.

- While most of these types of ejections happen to individual stars randomly, it can happen on occasion that two stars in different parts of the cluster undergo such an ejection at nearly the same time and in nearly the same direction. When that happens, the two ejected stars, which initially had nothing to do with one another, become joined by gravity as an ultrawide binary system.

- The widest of these ultrawide binary systems is much, much wider than the stellar wombs in which stars are normally born, and instead have separations similar to the typical sizes of open clusters. This is not a coincidence. It is a direct consequence of these binary systems having been brought together through the mutual-ejection mechanism.

Prospects for Habitability

- Planets are much more likely to arise in open clusters than in globular clusters. That's because the chemical composition is more complex—and, therefore, more supportive of life—in the open clusters. And that's because the open clusters have formed more recently from chemically enriched material, which includes the ashes of previous stellar generations.

- At the same time, even open clusters represent relatively densely populated environments. Certainly, they are more densely populated environments than a random isolated point in space, such as where our own solar system currently resides. So, planets that find themselves in solar systems within open clusters will be more likely to be disrupted by jostling from other stars in the cluster. Any planets that become stripped from their parent stars would then float freely through the cluster—what we refer to as solivagant planets.

- Imagine a civilization on a planet happily in orbit about a sun in an open cluster. The night sky would be filled with extremely bright stars, similar to our full Moon. Now imagine the havoc wreaked if that planet then became stripped away from its sun. Deprived of life-giving light and heat, surely this would spell disaster for the planet, doomed to drift through the rest of the cluster, a lifeless barren world that was.

- Imagine what life might be like on a planet in a globular cluster. While the elemental compositions of stars in a globular cluster don't favor the formation of rocky worlds or life on them, it might still be possible.

- Imagine a sky filled with not a single sun but hundreds or thousands all around. Astronomers have, in fact, found a planet in a globular cluster that orbits a binary star system and is 13 billion years old. In this case, the two suns are a white dwarf and a neutron star, one the corpse of a low-mass star and the other the corpse of a massive star.

Suggested Reading

Archinal, *Star Clusters*.

HubbleSite, “Star Clusters.”

Questions to Consider

1. In what ways are star clusters uniquely important for piecing together the time line of the life cycles of stars?

2. What might be some of the reasons that globular star clusters of the type seen in the halo of our galaxy are no longer formed? Why does the galaxy now make only open clusters?

A Portrait of Our Star, the Sun

Lecture 12

In this lecture, you will take an imaginary trip into the Sun—a star firmly in the midlife stage—as if plunging in at the top and diving down to its core, and you will learn about the different layers of the Sun's interior as you do so. Then, you will take a step back out to explore the phenomena occurring on the Sun's surface and the effects of these phenomena on humans on Earth.

Diving into the Sun

- Obviously, we can't actually dive into the Sun, but suppose that we could pull the feat off without the unfortunate consequence of incineration. The Sun is made entirely of gas, not liquid. But, even so, it is a sufficiently dense gas that it behaves like a liquid. For the purposes of our imaginary dive, thinking of the Sun as a liquid can be a helpful way of conceptualizing its fluid nature.

- The visible surface of the Sun is what we refer to as the photosphere. It is the glowing yellow surface that we see as the shining Sun in the sky. Like the surface of a swimming pool, the Sun's surface shimmers and undulates. However, unlike the water in a pool, the Sun's surface is opaque. It appears as a wall of light, and you can't see into it, let alone see down to the bottom.

- As you prepare to dive in, your first sensation would be that of an intense blast of heat. The Sun's temperature at its surface is about 6000 degrees Celsius—hot enough to melt any solid. But unlike a fluid, the Sun at its surface is extremely rarefied; it is comparable in density to air. And because the density at the Sun's surface is so low, you would experience no buoyancy, nothing to float you back up to the top. Instead, you'd sink faster and faster.

- In fact, just like falling through a cloud, you would simply free-fall. If you could continue to fall at this pace, it would take about 30

minutes to reach the center of the Sun 700,000 kilometers down. However, you wouldn't free-fall all the way down, because the Sun's density increases steadily toward its center.

- By the time you got about halfway down, the density would be comparable to water. And here, like being in a pool, it would require effort to push farther down against the buoyancy pushing you back up.

- If you could continue plunging downward toward the Sun's core, you'd push through increasingly dense fluid. Eventually, you'd be pushing through a fluid so dense that it would be like swimming through tar. Then, at the bottom, you'd be in fluid more than 100 times the density of water but that was still gas. This is because the physics of matter are such that a gas can remain a gas without solidifying, even at extremely high densities, as long as the temperature is high enough.

- Finally, down in the Sun's core, the temperature would be about 15 million degrees Celsius. This is the central furnace of the Sun, the place where the Sun's energy is ultimately generated through the process of nuclear fusion. And the nuclear fusion in the cores of stars like the Sun is the most important thing that stars in this stage of the life cycle do.

The Sun's Energy

- Floating back up to the surface, the first region of the Sun's interior that you'd pass through is the hot, dense core itself. The core comprises approximately 20% of the Sun's interior. This is the region where the energy that percolates its way to the surface is generated.

- From the core, the energy has to work its way toward the surface. But it can't just stream freely to the surface because it has to pass through layer after layer of dense, opaque gas. So, we say that the energy from the core is transported or carried from the core toward

the surface by a few different mechanisms. It takes a long time for the energy to be carried all the way to the surface.

- Emerging from the dense core, for the next 50% or so of the Sun's interior, we move through a region known as the radiation zone. In this region, the energy from the nuclear furnace at the core is carried principally in the form of light—or radiation.

- The gas comprising the Sun's interior in the radiation zone is essentially a static medium through which light energy passes. As we pass through this radiation zone, the Sun's density drops from about 10 times the density of water at the bottom to about a tenth the density of water closer to the surface.

- Next, we transition from the radiation zone into a region known as the convection zone. This is an important transition because here the energy percolating up from the bottom is no longer transported principally in the form of light. Rather, it is transported by bulk motion of the fluid. The gas roils and boils, producing large-scale

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Sunlight is solar radiation that is visible at the Earth's surface.

currents of movement similar to convective motions of magma beneath the Earth's surface.

- In fact, the upper 25% or so of the Sun's interior is dominated by these convective motions. Consequently, if buoyancy weren't strong enough to return us all the way to the surface in our imaginary journey, the convective motions would propel us the rest of the way.

- Finally, as we push back up through the photosphere and look back down, we see that the Sun's surface is not smooth and uniform but, rather, roiling all over, much like the surface of a pot of boiling water. These boiling motions of the Sun's surface are called granulation, because of how the churning surface appears from Earth.

- Now that we've reemerged from the Sun's interior in our imaginary swim from the center to the surface, let's consider how the energy generated in the Sun's core percolates its way out. The energy that we ultimately see as the Sun's bright yellow glow at its surface is generated down at the bottom, in the Sun's core, through the process of nuclear fusion.

- The energy rising from the Sun's core takes a while to percolate to the surface because the energy, in the form of light, cannot simply stream out through the dense interior. Rather, it slowly diffuses its way out. The light energy generated in the core travels a very small distance before being absorbed in the surrounding layer, then reemitted, then reabsorbed, and so on.

- Finally, that energy emerges from the surface, about 17,000 years after it was initially produced. If the Sun were to suddenly stop generating energy right now, it would continue to shine for 17,000 years before the photons produced just now finally worked their way to the surface.

- The surface of the Sun that we see glowing a bright yellow—the photosphere—is not the end of the story. In fact, the Sun's influence extends far beyond the photosphere, as the roiling of the Sun's

surface causes heat to be steadily injected into the Sun's hot, tenuous (meaning "low density") outer layers called the chromosphere and corona.

- The chromosphere is located immediately above the Sun's photosphere. It emits a distinctly red pigment caused by the fact that, whereas the photosphere emits a continuous rainbow of colors, the chromosphere's tenuous nature causes it to emit only certain specific colors of light. One of the most prominent colors that it emits in visible light is a bright red color emerging from highly heated hydrogen atoms.

- We don't ordinarily see this red light from the chromosphere because the chromosphere is very tenuous compared to the photosphere and emits very faintly in comparison. Its light is normally drowned out by the glare of the photosphere, but during a total solar eclipse, the chromosphere can become visible to the naked eye.

- The chromosphere is estimated to be approximately 20,000 degrees—so hot that this tenuous layer of gas emits primarily ultraviolet light. In fact, this is where most of the Sun's ultraviolet light is produced. Thankfully for us, most of it is absorbed by the Earth's atmosphere, limiting the damage it can do to our skin and eyes.

- Above the chromosphere is an even hotter layer called the corona, which is extremely hot—about 2 million degrees Celsius. At such an extremely hot temperature, it emits primarily X-ray light. Even so, the corona can be seen in visible light, but because it's extremely tenuous, it glows dimly and can be seen only during a total solar eclipse.

The Sun's Magnetic Nature

- The Sun's surface is frequently pocked with dark spots that we call sunspots. These spots are darker than the surrounding surface because they represent cool regions—typically a few hundred degrees cooler than the rest of the photosphere—so, by virtue of being cooler, they emit less light.

- Sunspots represent the footpoints of the Sun's magnetic field—the points on the Sun's surface where the magnetic field pokes out and pokes back in. Magnets always have a north pole and a south pole. Sure enough, sunspots almost always appear in pairs. The sunspot pairs correspond to the north and south poles of a strong localized magnetic field on the Sun. The Sun as a whole has a magnetic field that behaves similarly to the Earth's magnetic field.

- However, because the Sun behaves like a fluid, its global magnetic field is constantly twisted and distorted by the Sun's rotation. This twisting causes the Sun's magnetic field to become kinked, and the places where these magnetic kinks occur are the places where the magnetic field pokes up through the surface, creating one sunspot, and back down into the surface, creating the paired sunspot.

- The kinked magnetic field poking up and back down through the surface causes the upwelling heat from below to be impeded at those points. Consequently, the surface at these spots becomes cooler than the surrounding surface, and we end up with a pair of cool—hence, dark—sunspots.

- The same magnetic field, if it becomes sufficiently kinked, can protrude far above the surface. This protruding magnetic field can be seen in the form of what we call prominences, gigantic loops that carry hot gas from the photosphere up into the surrounding layers. In extreme cases, these prominences can be quite large, elevating hot gas to heights of a tenth or more of the Sun's radius above the surface.

- When these magnetic loops erupt, not only does an erupting prominence inject gas and heat into the corona, but it can also release its energy violently enough to expel the heated gas far out into space. We call such an event a coronal mass ejection. These coronal mass ejections can fling the ejected gas as far as the Earth and beyond, producing a gust that we call a solar storm, which we see on Earth as aurorae and which can even knock out communications satellites in Earth's orbit.

- These erupting magnetic fields on the Sun generate an enormous amount of heat, producing flashes of X-ray radiation called flares. When these extremely powerful X-ray flares erupt, we often see particularly strong “gusts” of gas launched out from the Sun. Fortunately for us, such extreme flares and coronal mass ejections are rare. Much more common are the more modest “puffs” of gas ejected from the Sun.

- Together, the strong gusts and the weaker puffs lead to a steady stream of gas flowing from the Sun’s surface out into the solar system. We refer to this stream as the solar wind. This wind, which permeates interplanetary space, flows fastest from the Sun’s north and south poles, with a speed of some 1000 kilometers per second. This wind extends the Sun’s influence far from its surface to the farthest reaches of the solar system.

Suggested Reading

Big Bear Solar Observatory, “Solar Movies.”

Simon, *The Sun*.

Questions to Consider

1. In what ways does the Sun represent our best opportunity for understanding the inner workings of all stars?

2. Try to imagine what the core of the Sun would “feel” like if touched. Consider its density, yet the fact that it is a gas. Would it be hard or soft? How would it compare to the hardest solids?

$E = mc^2$—Energy for a Star's Life

Lecture 13

In this lecture, you will learn about the process by which the Sun shines, and by extension, you will come to understand how all stars shine. The Sun is a "nuclear factory," alchemizing the simplest of all elements, hydrogen, into helium and carbon—the same carbon that is the basis of all life. This is the result of a mighty struggle against gravity, a matter of life or death for the Sun. It's a 10-billion-year struggle that the Sun, through the power of $E = mc^2$, is able to withstand for awhile.

The Energy of Our Sun

- For its entire existence—from its birth and throughout its life and, finally, to its death—the Sun is wholly given over to a mighty battle, and this mighty battle is to hold itself up against the unrelenting crush of gravity.

- As long as the Sun possesses mass—and the Sun has a mass equivalent to one million Earths—gravity will not relent. Unless the Sun stands up for itself, gravity will crush it into nonexistence. So, for as long as it is able, the Sun does the only thing it can do to survive, which is push back. The Sun produces heat, which creates outward pressure against the compressing force of gravity.

- The Sun shines a total of 400 trillion trillion watts. The source of the Sun's immense energy output is connected to its immense mass. Energy (E) is the same as mass (m) times a conversion factor (c^2, which is just a number): $E = mc^2$. In essence, this equation—Einstein's most famous equation—says that mass is energy.

- This is a deeply profound idea. We normally think of matter and energy as fundamentally different entities. Matter is the "stuff" of the world, whereas energy is what makes it go. However, this equation says that, in fact, matter is another form of energy. Therefore, mass, being a form of energy, can be turned into another

form of energy, such as heat or light. That's what stars do; they convert mass to energy. And the way they do it is nuclear fusion.

- To understand why converting matter into energy can create so much energy as to generate 400 trillion trillion watts for billions of years, we have to appreciate the conversion factor, c^2, which is the speed of light—a fundamental constant of nature. It's a really big number: 300 million meters per second. Now, square 300 million, and you've got an enormously big number: 90,000 trillion. In other words, converting even a tiny amount of matter produces a lot of energy because the conversion factor that relates matter and energy is so big.

Nuclear Fusion

- The basic process by which the Sun taps into the power of $E = mc^2$ is the fusion of light elements into heavier elements. Fusion is the process of sticking atoms together to make heavier atoms. This is not the chemical process of attaching separate atoms to one another to make molecules, such as 2 hydrogen atoms and 1 oxygen atom making water molecules, H_2O; rather, it is the welding together of the *nuclei* of atoms to make entirely new, heavier atoms—new elements.

- Fusion requires enormous pressure, which so far is only achievable at the centers of stars. It turns out that sticking the nuclei of atoms together involves a loss of mass, which is released from the newly formed atom in the form of very energetic light.

- The simplest example of this process is the fusion of hydrogen (element number 1 on the periodic table) into helium (element number 2 on the periodic table). In fact, this is the very process that fuels the Sun now and fuels most stars for most of their lives. The Sun, like most stars, is 75% hydrogen, so it has a lot of hydrogen to work with.

- The nucleus of a hydrogen atom is very simple: a single proton. The nucleus of a helium atom is only slightly more complex: two

protons and two neutrons. The masses of protons and neutrons are very, very similar, so for now, you can think of a helium nucleus with its 2 protons plus 2 neutrons as being akin to 4 protons.

- In fact, the fusion process involves sticking 4 hydrogen atoms together; 2 of the 4 hydrogen protons become neutrons in this process. The end result of the process is that the 4 hydrogen atoms have fused to form a single helium atom—that is, 1 atom with 2 protons and 2 neutrons in its nucleus.

- Let's compare the total mass of 4 hydrogen atoms to the mass of 1 helium atom. They should be the same—right?—because the 4 hydrogen atoms were used to make the 1 helium atom. A hydrogen atom has an atomic weight of a little over 1, and a helium atom has an atomic weight of a little over 4, so a helium atom weighs almost exactly 4 times as much as a hydrogen atom—but there is a slight discrepancy. In fact, a helium atom weighs about 0.7% less than what 4 hydrogen atoms weigh. It's a tiny difference, but it makes all the difference.

- The act of manufacturing helium out of hydrogen trades a small amount of mass into a lot of energy: c^2. This energy keeps the Sun hot enough to keep up the tremendous pressure required to push back against gravity, which has not stopped squeezing. In addition, now the Sun has 4 fewer hydrogen atoms and 1 more helium atom than what it started out with. The Sun is alchemizing itself, turning itself from an immense ball of hydrogen into an immense ball of helium—about 0.7% less immense, but still less immense.

- This basic process of fusing hydrogen atoms into helium atoms can supply a star's power needs for a long time. For a star like the Sun, it can go on for about 10 billion years, but once the supply of hydrogen fuel is consumed, the Sun will stop making nuclear energy. And at that instant, without missing a beat, gravity is there, already pouncing, bearing down to try to crush the Sun.

The Periodic Table of the Elements

Period \ Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H 1.008																	2 He 4.003
2	3 Li 6.941	4 Be 9.012											5 B 10.81	6 C 12.01	7 N 14.01	8 O 16	9 F 19	10 Ne 20.18
3	11 Na 22.99	12 Mg 24.31											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.07	17 Cl 35.45	18 Ar 39.95
4	19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.88	23 V 50.94	24 Cr 52	25 Mn 54.94	26 Fe 55.85	27 Co 58.47	28 Ni 58.69	29 Cu 63.55	30 Zn 65.39	31 Ga 69.72	32 Ge 72.59	33 As 74.92	34 Se 78.96	35 Br 79.9	36 Kr 83.8
5	37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc (98)	44 Ru 101.1	45 Rh 102.9	46 Pd 106.4	47 Ag 107.9	48 Cd 112.4	49 In 114.8	50 Sn 118.7	51 Sb 121.8	52 Te 127.6	53 I 126.9	54 Xe 131.3
6	55 Cs 132.9	56 Ba 137.3	57 La 138.9	72 Hf 178.5	73 Ta 180.9	74 W 183.9	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.1	79 Au 197	80 Hg 200.5	81 Tl 204.4	82 Pb 207.2	83 Bi 209	84 Po (210)	85 At (210)	86 Rn (222)
7	87 Fr (223)	88 Ra (226)	89 Ac (227)	104 Rf (257)	105 Db (260)	106 Sg (263)	107 Bh (262)	108 Hs (265)	109 Mt (266)	110 Ds (271)	111 Rq (272)	112 Uub (285)	113 Uut (284)	114 Uuq (289)	115 Uup (288)	116 Uuh (292)	117 Uus 0	118 Uuo 0

6	58 Ce 140.1	59 Pr 140.9	60 Nd 144.2	61 Pm (147)	62 Sm 150.4	63 Eu 152	64 Gd 157.3	65 Tb 158.9	66 Dy 162.5	67 Ho 164.9	68 Er 167.3	69 Tm 168.9	70 Yb 173	71 Lu 175
7	90 Th 232	91 Pa (231)	92 U (238)	93 Np (237)	94 Pu (242)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (249)	99 Es (254)	100 Fm (253)	101 Md (256)	102 No (254)	103 Lr (257)

- And for a little while, it will. The Sun's core will shrink under its own weight, becoming even denser than before. But then, $E = mc^2$ will come to the rescue again, as the Sun finds itself sufficiently hot and dense to be able to once again perform nuclear fusion, now sticking helium atoms together—the same helium atoms that the Sun previously fabricated from hydrogen.

- Here, the basic fusion process turns 3 helium atoms into 1 carbon atom—each helium atom contributes 2 protons and 2 neutrons, so that makes a total of 6 protons and 6 neutrons, which is what carbon is. In fact, a carbon atom weighs a tiny bit less than the combined weight of 3 helium atoms. Once again, in the process of making a heavier atom from lighter ones, a little bit of mass is traded in for pure energy.

- Once the fusion of helium into carbon has run its course, gravity takes over once again, and this will lead to the Sun's demise. It will begin to slough off its outer layers, sprinkling carbon atoms into the surrounding cosmos. Meanwhile, its core is crushed down by gravity into an unimaginably dense and inert ball of carbon atoms—a massive diamond in the sky. Those diamonds in the sky, called white dwarf stars, have their own amazing story.

Seeing into the Sun

- There are two ways that astronomers can see into the Sun: by using strange particles called neutrinos and through the science of sunquakes (also known as helioseismology).

- The same process that the Sun uses to create energy from mass via $E = mc^2$—nuclear fusion—produces a strange particle called a neutrino as a by-product. One of the basic ways in which neutrinos are created is when a proton converts into a neutron, through a process known as beta decay. This is a part of the nuclear fusion process.

- Neutrinos are strange because they have almost no mass and move at nearly the speed of light. They are very difficult to detect. In fact, to detect them requires enormous underground particle detectors

involving massive amounts of ultrapure water. But they can be detected, and our neutrino detectors see a steady stream of them pouring out of the Sun.

- Because we know how much energy the Sun produces, and we know how much energy is released in each nuclear fusion reaction, we can calculate how many of those by-product neutrinos should be produced.

- The number of neutrinos we see is the same as the number we expect if nuclear fusion is occurring at the rate required. The fact that we see solar neutrinos at all, and the fact that we see the right number of them, is a powerful confirmation of our basic understanding of nuclear fusion as the engine of why the Sun shines.

- Sunquakes are another powerful probe of the Sun's interior. A good analogy for this is earthquakes on the Earth. Earthquakes are one of the most important ways that scientists are able to determine what the interior structure of the Earth is like. That is because earthquakes produce sound waves that travel through the Earth, and the manner in which those sound waves propagate tells us the physical properties—such as the density—of the material through which they travel.

- A similar thing happens on the Sun—only it happens continuously. Hot gas at the surface of the Sun is constantly roiling and bubbling. Heat from below pushes the gas up; then, the gas cools and drops back down. This type of undulation produces the roiling motions of the Sun's surface, similar to boiling water in a pot, called granulation.

- This constant undulation of the Sun's surface causes it to vibrate, It "rings" like a bell. And just as a large, thick bell vibrates with a low tone whereas a small, thin bell vibrates with a high pitch, these vibrations tell us about the properties of the Sun's interior, such as its density. You can think of these vibrations as sound

waves, because that is what they are: acoustic waves that propagate through the Sun's interior.

- When we observe the oscillations of the Sun's surface, we see a specific pattern of frequencies, just as we do when we hear the ringing of a bell. And these, in turn, give us information about what the density and temperature of the Sun is throughout its interior.

- Scientists have used the Sun's vibrations to graph the density of the Sun. When they compare the density that they measure through sunquakes to the density as predicted by the fusion model, there is exquisitely good agreement. Just as neutrinos confirm that nuclear fusion reactions occur in the Sun, sunquakes confirm that the physics of nuclear fusion must be responsible for the Sun's internal structure.

Suggested Reading

Bodanis, $E = mc^2$.
IceCube Neutrino Observatory, "IceCube Neutrino Observatory."

Questions to Consider

1. What are the most significant pieces of direct evidence from the Sun that confirm our basic understanding of nuclear fusion as the source of the Sun's power and of the internal structure of the Sun?

2. Having learned that energy and mass are actually equivalent, and having discussed how fusion converts a bit of mass into a lot of energy, how might one tap into the equivalence of mass and energy the other way around? What would it mean to convert energy into mass?

Stars in Middle Age

Lecture 14

In this lecture, you will learn about stars during the stable, long-lived portion of their life cycle that we call the main sequence stage. During this stage, the stars are able, through the energy they generate in fusion reactions, to hold strong against gravity. However, as they use up their stores of fusionable material, they undergo a series of shorter-lived resuscitations, during which they are briefly able to withstand gravity again for a time before they finally die. Importantly, it is in the resuscitations that stars experience before death that the stars manufacture many of the elements so essential to us, including carbon and oxygen.

The Stefan–Boltzmann Law

- Recall that the Hertzsprung–Russell diagram is a graph in which the properties of stars are represented by their temperatures on the horizontal axis and their luminosities on the vertical axis. One of the most important features of this diagram is what we call the main sequence, a diagonal swath on which 90% of stars are found.

- All stars begin their lives at some place on this main sequence. Precisely where is determined by their mass—their birth weight. And because stars spend about 90% of their lifetime on the main sequence, this means that the mass of the star determines the temperature and luminosity that the star will have throughout the majority of its life.

- In addition, a star's temperature and luminosity together determine its size through a relationship called the Stefan–Boltzmann law. That relationship states that the total luminosity of a star, L, equals the amount of light radiated by each square meter of the star's surface times the total number of square meters of surface area the star has.

- The total amount of energy radiated by 1 square meter of the star's surface is given by Planck's radiation law, which says that E (the amount of light radiated each second by 1 square meter of radiating surface) is a constant, σ, times the temperature to the 4th power: $E = \sigma T^4$.

- That's the energy of 1 square meter. How many square meters are there in the surface of a star? That's just the surface area of a sphere, A, which is 4 times pi (π) times the radius squared. Altogether, the Stefan–Boltzmann law says that the total luminosity of the star is L, which is the product of the luminosity per square meter, E, times the total surface area in square meters, A. And that equals σ times temperature to the 4th power times 4π times the radius squared: $E = 4\pi r^2 \sigma T^4$.

- Using this formula, the quantities graphed in the H–R diagram—temperature and luminosity—are together connected to the radius or size of the star. For a star of any particular combination of temperature and luminosity, you can solve the equation for the star's radius. The star's temperature determines how much luminosity it can radiate per square meter, so it has to have a certain radius in order to have enough surface area to radiate the total luminosity of the star.

- The star's temperature and luminosity are themselves determined by the star's mass. Remember that mass is a star's DNA. So, then, altogether the mass of the star is what dictates all three of these basic stellar properties: temperature, luminosity, and size.

- More practically speaking, the Stefan–Boltzmann law also means that for a star at any place in the H–R diagram, representing a specific combination of temperature and luminosity, we can directly infer the size of the star.

- Fundamentally, stars in different parts of the H–R diagram represent stars at different stages of evolution. Stars start on the

main sequence, then move up and to the right into red giants, and then finally swoop over the left and down into white dwarfs.

The Fusion of Helium into Carbon

- What defines the long-lived, main sequence stage of a star's life is that it has a sufficient amount of hydrogen in its core to be able to fuse helium, thereby generating the energy that it needs to create the heat and pressure required to hold itself up against gravity. That state of gravitational equilibrium is highly stable, and the star remains unchanged throughout this long middle stage of life.

- A star's mass determines where along the H–R diagram main sequence it will be. In addition, the star's mass determines how long the star will remain a main sequence star. In other words, how massive a star is determines how quickly it will use up the store of hydrogen in its core. It turns out that how quickly a star will use up the hydrogen in its core—converting it all to helium—depends on the square of the star's mass.

- To see why this is, there are two factors to consider. First, how much energy can a star of a given mass produce through fusion? Second, how quickly does that star use up its fusion energy? The first factor is dependent simply on the mass of the star: The more massive the star, the more massive its core, and the more hydrogen mass is available to convert into helium. So, all things being equal, a more massive star has more fuel to burn.

- But all things are not equal. A more massive star burns its fuel more fiercely. To be specific, the luminosity of a main sequence star is proportional to its mass to the third power. So, a more massive star has more mass to burn, but it burns through that fuel much, much more quickly. With one factor proportional to the mass and the other factor proportional to the mass cubed, we end up with a final answer of the lifetime of the star being inversely proportional to the mass squared.

- For stars of the Sun's mass and heavier, their lifetimes are—relative to the age of the universe—finite. There comes a time when these stars use up the store of hydrogen in their core, having converted it all to helium. The most massive stars do this very rapidly; the less massive stars do it more slowly. But for all of these stars, they do run out of gas, and the end does come.

- The first thing that happens then is that the star stops fusing hydrogen into helium. And at that instant, gravity, which has been there all along, bearing down on the star, begins taking advantage of the star's reduced heat output and begins choking the star, shrinking its core toward oblivion.

- But this squeezing actually acts to give the star new life, at least for a short time. By compressing the star's core, which is now made of helium, gravity heats up the star's core to an extremely high temperature. At first, this compression and heating causes the core to actually generate even more heat than it did when it was happily fusing hydrogen into helium. And that causes the core to levitate its outer layers so that they expand outward and the star as a whole swells even as its core is compressing.

- As the surface swells, it cools. So, we have a red giant star, cool at the surface but enormously luminous because of the immense surface area from which it can radiate. A relatively low-mass star like our Sun will become such a red giant. A much more massive star will undergo the same process but, by virtue of its even more swollen size and even more prodigious luminosity, will become what we call a red supergiant.

- What happens at this stage is that gravity has compressed and heated the core of the star to such a degree that a new round of nuclear fusions is able to ignite. Only this time, instead of hydrogen being fused to helium, we have 3 helium atoms being fused together to make 1 carbon. The resulting carbon atoms weigh a bit less than the 3 helium atoms that make them up, leading to a conversion of mass to energy according to $E = mc^2$.

- The moment at which the fusion of helium into carbon ignites is sudden, and like defibrillator jolting a heart back into life, the star undergoes what is known as a helium flash. Instantly, the core pulses back to life as it is once again able to generate its own energy and heat with which to hold itself up against gravity. The star is now a stable red giant or red supergiant, depending on its mass.

- But this resuscitated state does not last for long, astronomically speaking. For a star like the Sun, which had managed to support itself through fusion of hydrogen into helium for 10 billion years, this stage lasts only about 10% as long—about 1 billion years.

- Why does the fusion of helium to carbon sustain the star for such a much shorter period of time compared to the hydrogen to helium fusion? The basic answer is that fusing helium to carbon is much less efficient at producing energy than is hydrogen to helium.

The Middle-Life and Near-Death Stages of Stars' Lives

- For a star like our Sun with a mass of 1 solar mass, the star begins its life on the main sequence of the H–R diagram. It will sit there happily for about 10 billion years. Then, as hydrogen in the star's core is exhausted and completely converted to helium, the star evolves to the right and up in the diagram, as it becomes a red giant star, its surface cooling but its luminosity increasing dramatically.

- When the red giant's core compresses enough to become hot enough to start fusing helium to carbon, the star shifts a bit to the left as its surface becomes a bit hotter, and the star stably fuses helium to carbon for a while.

- Finally, once the helium is fully depleted and converted to carbon in the core, the star again shifts up and to the right, becoming a cool but extremely luminous red giant, and then at last sheds its outer layers as a planetary nebula, revealing the inert, hot carbon core, which becomes a white dwarf at the far lower left in the diagram.

- In contrast, for a much more massive star—for example, a star 10 times the mass of our Sun—the star again starts out on the main sequence. However, as it completes each stage of nuclear fusion, it swings far to the right, its surface much cooler but still at a very high luminosity—a red supergiant.

- As each successive stage of nuclear fusion initiates in the core, the star briefly returns back toward the main sequence, but not all the way. It appears as a yellow supergiant. The star swings back and forth in the diagram multiple times as the star proceeds through different stages of nuclear fusion. Finally, once the star has fused all the way to iron in the core, the star goes supernova and disappears from the H–R diagram.

Suggested Reading

DeVorkin, *Henry Norris Russell*.

Las Cumbres Observatory Global Telescope, "Hertzsprung–Russell Diagram Simulator."

Questions to Consider

1. Why do stars spend so much of their lives, about 90%, on the main sequence in the Hertsprung–Russell diagram? What is happening within them that makes them so stable for so long?

2. In what ways is the H–R diagram, and the main sequence in particular, important to astronomy beyond the life cycles of stars?

Stellar Death

Lecture 15

In this lecture, you will learn about the wondrous, beautiful, and dramatic deaths of stars. Approximately 90% of all stars will end their lives in the silent majesty of a planetary nebula, sprinkling their ashes—including those essential carbon atoms—into the surrounding space. The rest of the stars, the most massive stars, will end their lives dramatically and cataclysmically in supernova explosions. In these explosions, the nuclear products of the stars' lives, including elements as heavy as iron, are sprayed into the surrounding space. And in their fiery deaths, the rest of the elements of the periodic table are synthesized. From these ashes, new life—all life, as we know it—emerges.

Planetary Nebulae

- Planetary nebulae, representing the scattered ashes of dead stars, are not only wondrous to behold, but they are also the mechanism by which stars, in their deaths, supply the cosmos with the legacy of their productive lives, sprinkling the surrounding space with carbon atoms that can become gathered up in the next generation of forming stars to be used, perhaps, for life-forms such as ourselves. Indeed, these graveyards themselves can be the fertilized ground where new enriched stars can begin their lives.

- Planetary nebulae, unlike the name suggests, have nothing to do with planets. The first planetary nebulae to be seen were seen through early telescopes that did not have very good angular resolution. Those early images appeared like small fuzzy blobs of color—not too dissimilar from what some of the distant planets in our solar system looked like to those telescopes, such as the planet Uranus. Hence the name "planetary nebula," and the name stuck.

- Perhaps the most striking features of the planetary nebulae are their amazing colors and shapes. The intensity of light we see from different parts of the nebula is an indication of the amount of

emitting material along our line of sight in that part of the nebula. That's because the gas within the nebula overall is highly rarefied—what astronomers call optically thin. So, the light patterns that we see within the nebulae are tracing the underlying pattern of how the gases within the nebulae are distributed spatially.

- But this can lead to some misinterpretation. In some cases, a nebula's ringlike shape suggests a structure like a smoke ring when, in fact, what we're seeing is a bubble. It appears ringlike because the bubble is very thin, very tenuous. So, we see just a small amount of light from the thin part of the bubble directly in front of us—the approaching part of the bubble. In contrast, at the edges, the curvature of the bubble means that we see through more of the bubble in those directions, and with more light-emitting material along those lines of sight, we see more intense light. In other cases, the ringlike appearance really is a ring.

- More generally, what do the shapes and structures of planetary nebulae tell us about the physical mechanisms responsible for their creation? This is an active area of research, and there are still more questions than answers. But some exciting answers are emerging.

The Stellar Death Process for Very Massive Stars

- Remember that up through the point that the stars become red giants fusing helium to carbon in their cores, the story for the highest-mass stars is the same as for the lower-mass Sun-like stars. However, after that point, the stories depart in important and dramatic ways.

- A massive star is able to repeatedly resuscitate itself through a series of rounds of fusion, each involving the products of the previous round, building up to heavier and heavier elements. Once the star is at the point that it is making iron in its core, it is finally at the end. That's because iron is the heaviest element that can be fused from lighter elements and still produce a bit of energy in the process.

- At this point, the interior of the star—now a supergiant—has a so-called onion structure. At the very center is the core, now made of

iron. Surrounding that is a layer of silicon fusing from the previous round of fusion. Around that is a layer of magnesium fusing. Around that is neon, then oxygen, then carbon, then helium. Each, like rings in a tree representing a record of the past, is a record of previous episodes of fusion. Finally, out beyond the helium layer, are the original outer layers of the star that never were involved in fusion in the core, remaining primarily hydrogen.

- With the core fused entirely into iron, fusion stops, and instantly, gravity pounces for the kill. The core of the star collapses in an instant. The manner in which gravity destroys the star is itself fascinating. This will end in a violent supernova explosion, but, counterintuitively, this first involves an implosion.

- At the very center of the core, the rapid collapse of the core causes the iron atoms to smash together and break apart into their constituent protons, neutrons, and electrons. This fission of the iron atoms actually saps energy from the core—for elements lighter than iron, the fusion process actually requires energy to be put in—so this only accelerates the star's demise.

- Finally, the newly liberated protons and electrons come together to form neutrons. Besides these new neutrons, there are also all the other neutrons that were liberated from the disintegrated iron atoms. Essentially, the result is that the rapidly collapsing core is turned into pure neutrons. Neutrons, by virtue of being electrically neutral, do not repel one another the way that ordinary matter does, so a ball of pure neutrons can collapse down to become the densest form of matter known: a neutron star.

- This process of rapid collapse of the star's core into a superdense neutron star happens so quickly that it is only after the creation of the neutron star that the outer layers of the star realize that the floor has dropped out from under them. So, the outer layers now begin to fall inward. The layer immediately around the neutron star at the center falls in first. When it reaches the new floor, the ultrahard

surface of the neutron star, it bounces back outward toward the next layers, which are still free-falling in.

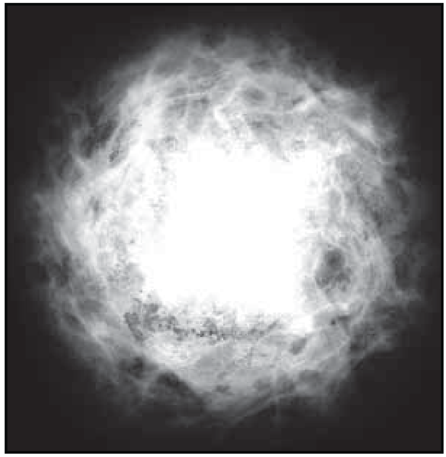
- This creates a powerful collision, which drives the material rapidly outward only to encounter the next layer free-falling in, and so on—until, finally, the collective wallop of these collisions drives the entire corpus of the star exploding out into space. That is a supernova explosion, and it all starts with an implosion and a bounce.

- A supernova explosion is the most energetically powerful event in the universe after the big bang. At the moment of the supernova, and for weeks thereafter, the explosion shines with more luminosity than all of the rest of the stars in the galaxy shining combined. That powerful explosion blows the body of the star to smithereens, expelling it into space and leaving behind the neutron star at the center of the hot, expanding shell of gas. Years later, the still-expanding shell of gas is what we refer to as a supernova remnant. These remnants have a beauty all their own, similar in some respects to beautiful planetary nebulae.

- Some supernova remnants are very disordered in appearance, whereas others are more symmetric, more orderly. It turns out that the more symmetric ones arise from the detonation of a white dwarf star. The less symmetric ones come from the demise of a massive star through the death process that has been presented in this lecture. Massive stars die violently and somewhat ungracefully.

- The most recent supernova to have been seen in the vicinity of our galaxy, although technically not within our galaxy, was in 1987. That supernova went off in one of the Milky Way's satellite galaxies, and it was near enough that we've been able to study it in exquisite detail since the initial explosion. From its asymmetry, it's pretty clear that it was a massive star that met its end when the fusion process concluded. And in this case, we have the advantage of images of the star before it exploded, confirming that the progenitor was a massive star.

- These massive-star supernova explosions continue to be important even after the explosion itself. In fact, it is only in the aftermath of these supernova explosions that all of the elements of the periodic table heavier than iron are produced. Why does that happen? The basic answer is because it can.



One way a star can die is in a supernova explosion, in which elements are sprayed into the surrounding space.

- Fusion of elements heavier than iron from lighter elements requires an input of energy. During the life of a star, it wouldn't make any sense for the star to perform such heavy-element fusion because the star would be sacrificing the very energy that it is desperately trying to produce in order to keep itself alive against the crush of gravity.

- But, now that the star is dead, and with an overwhelming abundance of energy available in the supernova explosion, these energy-costly fusion reactions can and do occur—for no other reason than that they are not prevented from occurring.

- These advanced-fusion reactions have to wrap up quickly, because the enormous free energy of the supernova is rapidly dissipated. Consequently, these very heavy elements—from cobalt and nickel to uranium—end up occurring in only trace amounts. However, some of these trace elements, such as copper and zinc, are important for life. In the very deaths of these massive stars we find the very zest upon which life as we know it depends.

Suggested Reading

Jastrow, *Red Giants and White Dwarfs*.

Kwok, *Cosmic Butterflies*.

Questions to Consider

1. How does the fact that a low-mass star becomes a red giant prior to its death actually make it easier for the dying star to gently expel its planetary nebula?

2. A planetary nebula virtually always has a white dwarf as it center, but there are examples of supernova remnants that do not have a neutron star at the center. How might that happen?

Stellar Corpses—Diamonds in the Sky

Lecture 16

In this lecture, you will learn about each of the three different types of stellar corpses: white dwarfs, neutron stars, and black holes. As you will learn, these stellar corpses continue to battle with gravity, an ongoing struggle that follows the stars into and beyond the grave. These amazing objects reveal an entirely new class of physical laws, from the microscopic physics of quantum mechanics to the fantastic new realm of gravitational wave physics.

White Dwarfs and Neutron Stars

- Our first stop in the stellar graveyard are white dwarfs, which are the exposed cores of stars like the Sun that have since died, puffing out beautiful planetary nebulae. White dwarfs are tightly packed, extremely dense balls of carbon, which is what the red giant star had fused from helium atoms in the final resuscitation of its life. White dwarfs have half of a Sun's mass of carbon packed into a volume the size of the Earth. Truly, these are diamonds in the sky.

- When first exposed as the dead star releases its outer layers into an expanding planetary nebula, the white dwarf is extremely hot, approaching a million degrees. Then, it slowly cools, as its heat is steadily radiated away. That is the fate of the white dwarf—to sparkle with ever less luster, eventually fading from view forever. However, there is a very special circumstance under which a cold, dead white dwarf can shine brilliantly one last time.

- Our next stop in the graveyard is neutron stars. Despite the name, these are not stars at all but, rather, the corpses of massive stars that have since detonated as supernovae. A neutron star is unimaginably dense. Ordinary matter, even matter as dense as lead, is almost entirely empty space. That's because in ordinary matter, the individual atoms are kept very widely separated by the electromagnetic repulsion of the electrons in those atoms.

The distance between the nucleus of an atom and its electrons is comparable in scale to the distance between the Sun and the Earth in our solar system.

- But in a neutron star, there is no repulsion between the particles, because there are only electrically neutral neutrons. So, the neutrons are essentially in direct contact with one another. In the entire universe, there is no form of matter more compact—that is, except for black holes. But unlike a black hole, a neutron star still has an actual physical size.

- A neutron star has anywhere from the mass of the Sun to 3 times that mass—remember that it started out as a very massive star—and has the physical size of about 10 kilometers, comparable to a midsize city. Whereas water has a density of 1 gram per cubic centimeter, and iron has a density of about 5 grams per cubic centimeter, and the core of the Sun has a density of about 100 grams per cubic centimeter, a neutron star has a density of about 100 trillion grams per cubic centimeter.

- Another remarkable feature of neutron stars is that they spin extremely fast. A slow neutron star spins perhaps once per second—which is fast when you consider that a neutron star weighs at least as much as the Sun and is the size of a city. A more typical neutron star spins 30 times per second. The fastest, known as the millisecond pulsars, spin almost 1,000 times per second.

- Why do neutron stars spin so fast? This is a consequence of the law of conservation of angular momentum. That law, similar to the conservation of energy, says in essence that the spin energy of an object is also conserved. The way this works is that a large object spinning slowly is equivalent to a small object spinning rapidly.

- A neutron star represents the highly collapsed, compressed remnant of a star that was a million times larger. That star may have spun relatively slowly, perhaps once per month or so. But now, that initial slow spin has been amplified a million times due to the million-fold

decrease in size. As fantastic as these objects are, the explanation for their amazing spin is really just fairly ordinary physics.

- But other aspects of the physical laws describing neutron stars and white dwarfs are anything but ordinary. White dwarfs and neutron stars, despite being dead, are nonetheless able to hold themselves up against the crush of gravity. These stellar corpses are highly compressed, having lost their ability to push back with the heat of fusion, but they still have a nonzero physical size. They hold themselves up through a bizarre form of pressure known as degeneracy pressure.

Degeneracy Pressure

- In ordinary matter, there is a direct relationship between the temperature of an object and the speed with which the atoms in it move. That energy of motion is the pressure of heat, and it is how stars push back against gravity ordinarily. But with degeneracy pressure, the motion of the particles in an object does not depend on the temperature or the heat content of the object. In fact, the object can be completely cold and still exert this type of pressure.

- One of the strange aspects of the physics of quantum mechanics is the Heisenberg uncertainty principle. Quantum mechanics in general is the set of physical laws that describe how matter behaves at the quantum level, at the microscopic level of individual particles. According to the Heisenberg uncertainty principle, it is not possible to simultaneously know the position and the speed of a particle with exactitude. The more exactly we localize a particle in space, the less certain we can be about its speed.

- As a particle's position in space becomes more tightly confined, the larger the spread in the possible speeds it can have. And the larger the spread in speeds that a group of particles has, the stronger the pressure exerted by those particles. The pressure exerted by a gas is determined by the speed of the fastest particles in the gas. Those fast-moving particles carry more energy of motion, and when they hit against something, they impart more energy in collision. That's

what pressure is—a collisional pushing of particles against one another due to their energy of motion. Faster-moving particles push harder; they exert stronger pressure.

- In the case of the Heisenberg uncertainty principle, the larger spread of particle motions means that there are more particles with faster motions, so overall the particles in the gas exert a stronger pressure. In other words, merely by packing particles closely together on the scale of individual particles—such as the space between neutrons in a neutron star—the speed of the particles increases, so the pressure they exert increases, increasing their ability to push back against gravity.

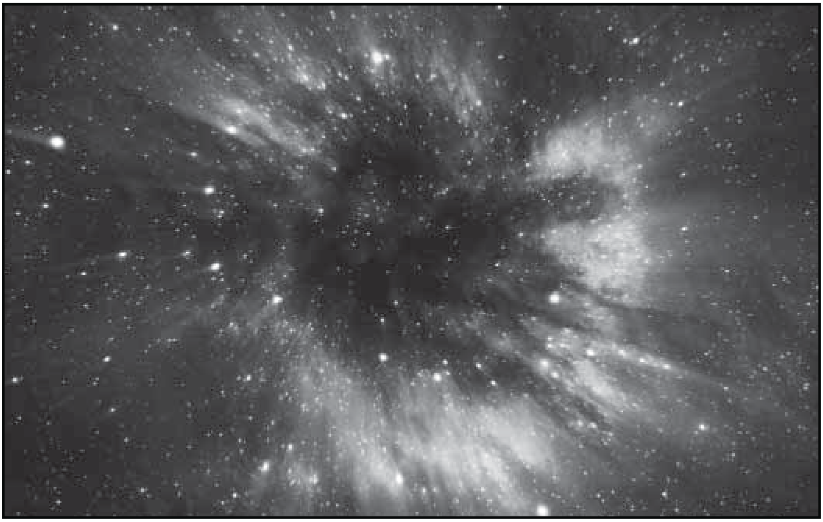
- In the case of a white dwarf, it is the collective microscopic action of the electrons in the carbon atoms that exert the degeneracy pressure to hold the white dwarf up. In the case of a neutron star, it is the collective microscopic action of the neutrons that exert the degeneracy pressure. Without this quantum mechanical pressure, these stellar corpses would become black holes.

Black Holes

- A neutron star cannot be any heavier than 3 times the mass of the Sun—any heavier and the degeneracy pressure is broken, and nothing can prevent gravity from finally having its way, crushing the star into nonexistence, creating what is perhaps the most fantastic object of all: a black hole. Black holes represent gravity's ultimate victory over a star, when even degeneracy pressure cannot save the star.

- Black holes don't have a size, but they do have mass. In fact, all of the mass that was there before the stellar corpse finally gave out is there still. Only gravity has crushed that mass down to zero size. Infinite density but finite mass is the incredible mind-bending nature of a black hole.

- There is a common misconception that black holes are lurking, menacing, predators just waiting to suck in anything and everything



The death of a massive star can form a black hole, which is a cosmic body of extremely intense gravity.

around them, like gigantic vacuum cleaners in space. In fact, in the immediate vicinity of a black hole, the laws of physics break down. There is a small region immediately around a black hole where the gravity of the black hole is so intense that not even light can pass by without being pulled forever into the black hole.

- The black hole's sphere of influence is described by the so-called Schwarzschild radius, which, for a black hole weighing the mass of the Sun, is 3 kilometers. In other words, inside of 3 kilometers, nothing—not even light—can escape, and within that space, we do not have the physics to describe the inner workings of the hole. But from a distance larger than the Schwartzschild radius, the black hole just feels like any other object with that same amount of mass.

- The Schwartzschild radius is sometimes also referred to as the photon sphere around the black hole. That's because, at that exact distance from the black hole, a photon of light would have

its ordinarily straight trajectory bent all the way around so that it would orbit the black hole.

- How do we know that black holes actually exist? After all, we can't see a black hole directly. It doesn't radiate because not even light can escape from within the Schwartzschild radius. However, we can use the light emitted by objects in the very near vicinity of black holes in order to indirectly weigh the black hole.

- Such systems are known as X-ray binaries. These are systems in which a black hole is orbited by another star and matter from the companion star spills onto the black hole. As it does, the spilling material spirals in faster and faster, like water spiraling down a drain, and in the process, heats up to such a degree that it radiates as X-ray light.

- By measuring the speed of the inspiraling material—using the Doppler effect—we can use the laws of physics to ascertain what the mass of the central object must be. Then, comparing the mass of the unseen central object with its size, as determined by the proximity that the inspiraling material achieves before falling in, we can determine whether the unseen object satisfies the Schwartzschild radius criterion for being a black hole.

- Looking to the future, there are efforts under way to develop an entirely new class of telescope that could someday detect the merger of two black holes. Some black holes may be part of binary star systems. Occasionally, those binary systems will involve "twins" that will both end up as black holes. Those sibling ghost stars would be completely undetectable, as neither can radiate light. However, they can in principle be detected with future gravitational radiation telescopes.

- Already, thanks to advances in very high angular resolution imaging with adaptive optics systems on large telescopes, we can directly study an extremely massive black hole that resides at the very center of our galaxy. That massive black hole probably formed

through the merger over time of smaller black holes going back to the formation of our galaxy as a whole.

Suggested Reading

Shapiro, *Black Holes, White Dwarfs and Neutron Stars*.

Tyson, *Death by Black Hole*.

Questions to Consider

1. How do the laws of quantum mechanics—the microscopic physics of individual particles—explain the nature of stellar corpses (white dwarfs and neutrons stars)?

2. Given the relative numbers of stars in the galaxy born with different masses, which of the different types of stellar corpses are the most common in our galaxy?

Dying Breaths—Cepheids and Supernovae

Lecture 17

Because stars very often begin their lives with siblings, they also often end their lives still bound to their siblings by gravity. The death throes of the longer-lived sibling can breathe new life into its long-dead sibling, for a brief but powerfully spectacular encore. In addition, the final moments of any star's life often involve hiccups and gasps, pulsations and mini-explosions, that provide some of our most valuable methods for measuring the distances to other galaxies and, therefore, have an importance to astronomy and to our understanding of the universe far beyond the stellar life cycle itself.

The Cepheid Instability Strip and Cepheid Variable Stars

- Less massive stars like our Sun end their lives as white dwarfs, the inert carbon remains of the core of the once-living star, now exposed at the center of a planetary nebula. White dwarfs are glittering diamonds that are destined to fade into obscurity as their ashes spread gently into space. More massive stars die dramatically in violent supernova explosions, the most energetic events in the universe, leaving behind a compact ball of pure neutrons—a neutron star—as the rest of the star is blown to smithereens, its material flung far and wide.

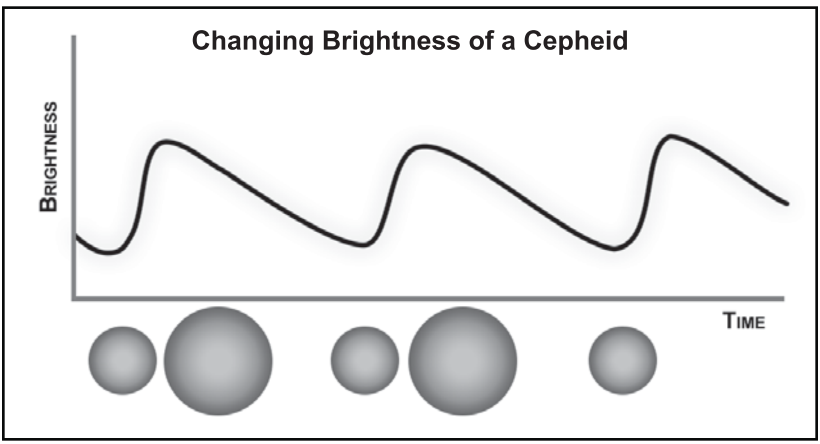
- In the lead-up to its death, before it becomes a white dwarf, a low-mass star goes through a stage in its life cycle when it is a red giant. At this stage, the surface of the star is swollen to an enormous size as helium begins to fuse into carbon in the core. For stars of a certain mass, about 2 or 3 times the mass of our Sun, they will pass through a special region of the Hertzsprung–Russell diagram as they evolve away from the main sequence toward becoming a red giant. This region is known as the Cepheid instability strip.

- The instability strip simply represents a particular combination of stellar properties—temperature and radius and luminosity—that

cause stars for a brief time to be pulsationally unstable. Whereas stars in their main sequence phase of life are stable, stars that have the physical properties to place them in the instability strip are unstable and are prone to oscillate strongly. These oscillations turn out to have an important predictable character that we can use.

- Stars like the Sun that are still in the main sequence phase of life are highly resilient and are able to maintain their composure in the face of adversity. If the star should experience any kind of disturbance, the overall properties of the star remain remarkably stable. That's because any minor change in the internal structure of the star is immediately compensated and corrected so that the star very quickly returns to its normal configuration.

- A star in the instability strip pulsates—it swells to become larger, and then shrinks to become smaller, then larger, then smaller, and so on. Accompanying this swelling and shrinking is a change in the star's luminosity. The temperature of the surface of the star doesn't change much during these oscillations, so the change in size directly leads to a change in brightness. When the star is larger, it is brighter; when it is smaller, it is fainter. These oscillating, pulsating stars are called Cepheid variable stars and RR Lyrae stars, named after the first stars to have been recognized as undergoing this phenomenon.



- An important consequence of these pulsations in dying stars is that they occur with a regularity that can be related to their average intrinsic luminosity. The regularity of their pulsations is called the pulsation period. By looking at a graph of the changing brightness of a Cepheid or RR Lyrae star, we can identify the pulsation period as the time between successive peaks in their brightness.

- Cepheid and RR Lyrae stars that pulsate with longer cadences are intrinsically more luminous than the more rapidly oscillating ones. This so-called period-luminosity relationship is incredibly useful and important.

- Because these pulsating stars are giants, they are bright, which means that we can see them over great distances. And because they pulsate in a steady fashion, it is easy to pick them out. And because their pulsation periods are in the range of 1 to 50 days, it is relatively easy to measure the period of pulsation for any given Cepheid or RR Lyrae star.

- Finally, by combining the measured period of pulsation with the known relationship between period and luminosity, their distances can be measured quite accurately. In fact, the first measurement of the distance to a galaxy other than our own was made possible through this technique.

- Soon after Henrietta Leavitt discovered and published the relationship between the Cepheid stars' pulsations and their luminosities, Edwin Hubble identified a Cepheid variable star in our neighboring galaxy Andromeda and was able to measure its distance. He did this by measuring the regular, periodic pattern of brightening and dimming in the stars over the course of several weeks.

- Hubble's discovery was the one of the first definitive pieces of evidence that galaxies like Andromeda were in fact island universes of billions of stars all their own, totally separate and vastly distant from our own Milky Way Galaxy. So, these dying breaths

of stars like the Sun have been an invaluable tool to our broader understanding of the universe.

- But if the stars provide crucially important service in their dying gasps, they can provide an even more important service after their deaths—that is, as long as they have a sibling companion star to bring them back to life for one brief, fiery, resplendent moment.

White Dwarf Supernovae

- When stars are born, they frequently—perhaps even most often—are born with at least one sibling. The two twins orbit one another, bound to one another by gravity. Beginning their lives as main sequence stars, the twins are relatively small, so they fit comfortably into the confines of their mutual orbit.

- Later on, the more massive of the twins ends its life, swelling to become a red giant, then sloughing off its outer layers as a planetary nebula, leaving behind the white dwarf corpse. The swelling of the senior sibling as a red giant may allow some of its material to spill onto the junior sibling, but this bit of sloshing of material does not fundamentally alter the course of the junior sibling's life. Perhaps it finds itself having inherited a bit more mass from its senior sibling, but the impact on the junior sibling's life cycle is minor.

- However, when it becomes the junior sibling's turn to face death, and it swells to become a red giant, the situation is very different. Here, material from the junior sibling spirals onto the white dwarf corpse of the first sibling, slowly adding mass to the white dwarf. At first, the addition of mass to the white dwarf simply crushes the already-compact white dwarf a bit more, as the white dwarf squeezes its carbon atoms evermore tightly in order to force the quantum mechanical degeneracy pressure to push back on the increased gravity more strongly.

- But once a sufficient layer of fresh material has accumulated on the surface of the white dwarf, a runaway burst of nuclear fusion can occur, turning the freshly accreted hydrogen from the donor

star rapidly into helium and carbon and causing the white dwarf to briefly shine brilliantly for perhaps a month or two. The amount of mass involved in these mini-eruptions is tiny, but it is enough to make the white dwarf's brightness increase by 100 times or more. The short brightening of the white dwarf can lead to the brief appearance in the sky of a new star, or *nova* in the original Latin.

- These novae are often recurring. As each episode of flash fusion completes, a next layer of fusionable material is deposited onto the now slightly more massive white dwarf, bursting again and again. These nova episodes continue until one of two things happen. Either the donor star ends its life to become a white dwarf as well, in which case the novae stop and the two dead siblings spend the rest of eternity in a ghostly dance. Or the senior sibling's white dwarf gets pushed over the brink, beyond the maximum mass that a white dwarf can sustain with degeneracy pressure. And if that happens, a very special and important event—a white dwarf supernova—occurs.

- A white dwarf supernova is a special type of supernova explosion that only occurs when a white dwarf stellar corpse is pushed over the degeneracy pressure limit by a binary companion star. These supernova explosions are important because they allow us to measure distances to the farthest reaches of the universe.

- The laws of physics allow a white dwarf to hold itself up against gravity by utilizing a strange form of pressure known as degeneracy pressure. Degeneracy pressure arises from the weird rules of quantum mechanics, which include a rule known as the Heisenberg uncertainty principle. That rule states that the more that particles become localized in space, the more uncertain their speeds become.

- Therefore, a white dwarf can force its constituent particles to move faster and faster by compressing the particles to greater and greater densities. This generates ever-greater pressure with which to push back against gravity. There is no heat involved in this—

just compression and the rules of quantum mechanics driving up the pressure.

- However, this process has a fundamental limit, which is the ultimate speed limit in the universe: the speed of light. This speed limit for the particles in a white dwarf corresponds to a certain maximum mass—namely, 1.4 times the mass of the Sun. That is the so-called Chandrasekhar limit for a white dwarf.

- Whereas a massive star's supernova can involve the detonation of a range of different amounts of material depending on the mass of the star, a white dwarf supernova always involves precisely the same amount of material—namely, 1.4 times the mass of the Sun. As a result, a white dwarf supernova always releases the same amount of explosive energy, because the same amount of explosives is involved every time.

- This property of a white dwarf supernova means that, if we have a way of reliably recognizing a white dwarf supernova as opposed to a massive-star supernova, then whenever we see one, we know precisely how luminous it is, and we can use that in comparison to how bright it appears to accurately determine the distance to it.

- The distance of objects in the sky can be calculated precisely using the inverse square law of light. This is, in fact, one of the most important tools by which astronomers measure accurate distances to some of the farthest galaxies. This works because supernovae are intrinsically the most luminous events in the universe, so they can be seen across the vast stretches of the universe. Thankfully, nature has provided a type of supernova that is always and everywhere the same—a benchmark.

- There are two ways to determine that one distant flash of light is the result of a white dwarf detonating as opposed to a massive star ending its life. The first way is to look at the light spectrum from the supernova flash. The vast majority of the body of the star involved in the explosion is the outer layers of the star, which were never

processed through the star's stages of fusion. That material is mostly hydrogen. Therefore, look at the light spectrum of a massive star's supernova, and you'll see very clearly the light features of hydrogen.

- The other way is to use the shape of the explosion. Long after the supernova goes off, the exploded material can be seen as an expanding shell of material that we call a supernova remnant—some of which are highly spherically symmetrical while others have much more complex morphologies. Research has shown that the white dwarf supernovae are measurably more symmetric than those produced by massive star deaths.

Suggested Reading

Bartusiak, *The Day We Found the Universe*.

Mann, *Shadow of a Star*.

Questions to Consider

1. What might be some reasons that more slowly pulsating Cepheid stars are also more luminous?

2. What might be some reasons that white dwarf supernovae produce more symmetric and spherical supernova remnants than massive star supernovae?

Supernova Remnants and Galactic Geysers

Lecture 18

The same cataclysmic explosions that signal the dramatic end of a massive star also serve to spread the chemically enriched remains of the star throughout the galaxy and help to trigger new generations of stars and solar systems. In this lecture, you will learn how the remnants of supernova explosions sculpt and compress the gas and dust between the stars. You will also learn that large numbers of exploding stars produce galactic geysers of chemically enriched material, which then rains back down onto the galaxy and provides the substance of new life.

Supernova Remnants

- There are two ways in which a star can end its life as a supernova. One way is that a white dwarf, the stellar corpse of a low-mass star like the Sun, may accumulate material from a sibling star until it reaches a critical mass and undergoes a thermonuclear explosion.

- The other way is when a massive star uses up its nuclear fuel, having alchemized in its core—starting from hydrogen—all of the elements up to iron. At that point, the star is unable to generate more fusion energy with which to hold itself up against gravity, collapses inward under its own gravity, and then explodes through a bounce mechanism. This type of supernova produces remnant expanding bubbles of hot gas that we can still see throughout our galaxy.

- When a star explodes as a supernova, it very energetically expels nearly all of the material that once made up the star's body. The expelled material pushes outward at an extremely high speed, as much as 30,000 kilometers per second, or about 10% of the speed of light. Because of that very energetic speed, the ejected material plows into the surrounding interstellar space supersonically.

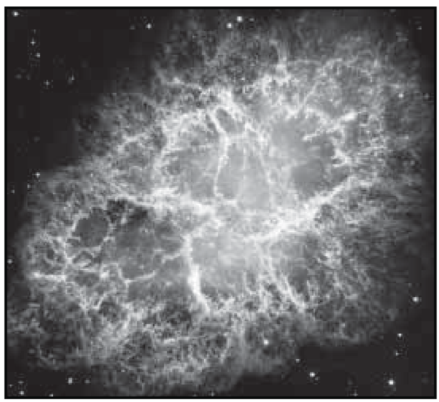
- As a result, a strong shockwave forms ahead of the expanding bubble of ejected material, and this shockwave heats the surrounding

galactic medium up to temperatures well above millions of degrees. That is so hot that the shock front emits strongly in X-ray light. The shock continuously slows down over time as it sweeps up the ambient medium, but it can expand over hundreds of thousands of years and over tens of light-years in size before its speed finally slows and comes to a halt.

- All supernova remnants go through a series of 5 stages as they expand into the surrounding interstellar space and then ultimately becoming incorporated into it. The first stage is the so-called free expansion stage, during which the ejected material sweeps out through its surroundings essentially unimpeded. This phase continues until the out-moving material sweeps up an amount of ambient material equal to its own mass. This can last up to a few hundred years, depending on the density of the surrounding gas.

- Second is the sweeping up of a shell of shocked interstellar gas. The supernova remnant bubble continues pushing outward, just somewhat more slowly than before. The strong shockwaves and hot shocked gas at the edges of the supernova remnant emit strong X-ray light.

- The third stage is called the snowplow phase, during which the shell of the supernova fireball begins to cool, forming a thin, dense shell surrounding the hot gas in the interior of the expanding bubble. The expanding bubble is slowing down during this third stage, but it continues to be propelled, like a snowplow, by the



The Crab Nebula, estimated to be 10 light-years in diameter, is an expanding remnant of a star's supernova explosion.

pressure of the extremely hot gas within. The gas and dust in the surrounding galactic medium is pushed together and gathered up, like snow and debris collected by a plow.

- In the fourth stage, the material in the supernova remnant's interior cools down, the bubble having expanded to a very large size. The shell around the bubble continues to expand from its own momentum, but slowly now, and the shell begins to break up, the overall supernova remnant becoming less intact.

- Finally, in the fifth stage, the material in the supernova remnant becomes gradually incorporated into the surrounding interstellar medium. At this stage, the supernova remnant has slowed down to a near stop, comparable to the slow speed of the random velocities of gas and dust particles in the surrounding medium. In total, about 30,000 years have elapsed since the initial supernova explosion.

- Because the supernova remnant interacts with the surrounding galactic medium through its plowing and compressing action, the supernova remnant can and does act as a trigger in some cases to initiate new stellar birth. That's because stellar birth takes place in clouds of gas and dust that have become sufficiently dense for gravity to take over and begin collapsing the material down to make new stars.

- With the supernova remnant plowing into its surrounding material, we have a perfect means by which otherwise diffuse galactic material is gathered up and compressed to the types of densities required for gravity to start the stellar birth process.

- The nursery that is giving birth to these stars now has much more in the way of elements such as silicon and iron to make rocks and oxygen to make breathable atmospheres in those newly formed worlds. In all likelihood, this is the type of scenario in which our own Sun and solar system—our Earth—came to possess the elements that make our rocky planet, its oceans, and our oxygen atmosphere possible.

- In the context of understanding how supernovae help to create and spread the heavy elements that are required for creating rocky worlds and for any life upon them, astronomers often need to be able know how a given supernova remnant was produced.

- There are two basic mechanisms for producing supernova explosions: One type of supernova results from the implosion then explosion of a massive star's death; the other type results when a white dwarf is pushed over its maximum possible mass by a sibling star spilling mass onto it. The two types of supernovae will both produce supernova remnants, but the amounts and proportions of heavy elements that they produce may differ.

- When we use computer analysis to quantify the degree of roundness and symmetry of each supernova remnant, we find that there is a stark, measurable difference between the two groups: The massive-star supernovae remnants are measurably more complex and less symmetric than the white dwarf remnants.

Super-Bubbles

- When multiple supernova explosions go off in proximity to one another, the result is an enormous type of supernova remnant that we call a super-bubble, which can dramatically influence the stellar life cycle across the entire galaxy. There are examples of such super-bubbles in our Milky Way Galaxy and in our nearest satellite galaxies. These structures can span enormous distances—up to 1000 light-years or more.

- From measurements of the vast dimensions of these structures and from measurements of the speeds with which they continue to expand in size, astronomers can estimate that these structures may represent the combined supernova remnant action of perhaps 10 or more supernova explosions all going off at nearly the same place and at nearly the same time.

- The stellar birth process might cause such an apparent orchestration of supernova explosions. When the stellar birth process in a stellar

nursery produces a cluster of stars—a stellar family—it tends to produce a distinct pattern of birth weights for the stars: lots of little runts and just a few behemoths.

- In most stellar nurseries, which birth perhaps 1000 stars or so, this translates into perhaps 1 or 2 stars massive enough to go supernova within the nursery. However, in some cases, a stellar nursery can birth perhaps 10,000 stars. In such cases, there may be a dozen very massive stars that will all die in supernova explosions. Because those massive stars were born at nearly the same time and from the same stellar nursery, they will die at nearly the same time and in that place—thus, driving a super-bubble.

- Super-bubbles push out into the surrounding space. They carve out large cavities in the surrounding galactic disk of gas and dust and push their hot, exploded stellar material up and out into the surrounding halo of the galaxy. From there, that material can then rain back down to the farthest reaches of the galaxy, where it can be gathered up again by gravity to form new generations of stars and planets.

- The effects of these super-bubbles on a galactic scale are most easily seen by looking at more distant galaxies, where we can take a panoramic view of an entire galaxy at once. The best case studies are galaxies seen edge-on from our perspective, because then we can use the glow of the billions of stars within that galaxy to illuminate from behind the large-scale structures caused by the super-bubbles.

Galactic Geysers

- Just as the geysers on Earth spew hot steam created from water heated beneath the surface up into the surrounding air, which condenses as mineral-rich water raining back down to the surface, helping vegetation to grow, galactic geysers spray hot gas from supernovae up into the galactic halo, which then condenses and rains back down as chemically enriched material to the disk of the galaxy, where it can fertilize new generations of stars.

- We can see the influence of such geysers in our own galaxy by observing the hot gas that fills our galaxy's halo and glows in X-ray light. Images taken with the Chandra X-ray telescope reveal not only that our galaxy's halo is filled to the brim with hot gas originating in supernova super-bubbles, but also that this hot gas extends far, far out from our galaxy. In fact, it completely envelops our galaxy, and beyond that, it completely envelops the Milky Way's satellite galaxies.

- This is important to our picture of how the life cycles of future generations of stars come to be enriched with more abundant heavy elements as produced in supernovae. The supernovae don't merely sprinkle their ashes hither and yon. More generally, the collective action of the many supernova explosions in the galaxy is to bathe, to engulf, the entire galaxy in those ashes, suffusing the galaxy with them.

- No wonder that a solar system such as our own, forming in the suburbs of the galaxy, has been so enriched with heavy elements that it was able to form a rocky, watery planet with enough organic material to permit abundant life.

- Maybe there are suburbs of other galaxies where the conditions for stars sufficiently enriched in heavy elements can form solar systems including rocky planets covered in liquid oceans and surrounded by breathable oxygen-rich atmospheres capable of supporting life as we know it. It is tempting to contemplate what a civilization on such a world at the outskirts of our galaxy or indeed in another galaxy—looking at our own suburb of the Milky Way, supernova remnants all around—might wonder about the potential for life around that otherwise ordinary yellow star we call the Sun.

Suggested Reading

Arnett, *Supernovae and Nucleosynthesis*.

Marschall, *The Supernova Story*.

Questions to Consider

1. In what ways do supernova explosions influence the life cycles of other stars, including those not yet born?

2. Astronomers sometimes describe galaxies as giant recycling plants. With respect to the life cycle of stars, in what ways is this description accurate, and in what ways is it not?

Stillborn Stars

Lecture 19

In this lecture, you will get to know the stars with the least potential, those that never make it as stars at all. Brown dwarfs for decades eluded discovery, but now we know that they do exist and that they appear to represent the failure of the stellar birth process. At the same time, these failed stars have taught us much about the stellar birth process and about the properties of stars more generally. It's little consolation to these stillborn stars, destined to fade totally into obscurity and darkness, but we've learned much from them about how and why nature sometimes succeeds, and sometimes fails, to birth a star.

Brown Dwarfs

- Not all stellar embryos ultimately make it as full-fledged stars. These recently discovered "failed stars," known as brown dwarfs, represent a strange type of netherworld, neither star nor planet. Put simply, a brown dwarf is an object that does not have enough mass to initiate nuclear fusion in its core. That mass turns out to be about 8% of the mass of our Sun.

- An object with a mass of just over 8% of the Sun's mass will turn on as a star, fusing hydrogen to helium in its core and going through the regular sequence of life stages for low-mass stars. But if an object emerges from the birth process with just a little bit less than that mass, it will never achieve the necessary temperature in its core to initiate fusion.

- Brown dwarfs are in many respects like Jupiter—relatively massive objects that, while not shining brilliantly as stars, do glow with the dim remnant warmth of their formation. So why don't we just call brown dwarfs planets?

- Fundamentally, a planet is an object that forms from the disk of gas and dust encircling a star and comes to orbit that star. A brown

dwarf, on the other hand, starts out going through the birth process of a star but, for some reason, doesn't emerge from the stellar womb with a high enough birth weight to make it as a star.

- At the same time, we can also separate brown dwarfs from planets based on their mass. Where Jupiter has a mass of 0.10% of the Sun's mass, brown dwarfs are generally regarded as having masses of at least 10 times Jupiter's mass. In other words, brown dwarfs are something betwixt and between stars and planets.

- The reason that there is a minimum mass that a brown dwarf can have is that, for brown dwarfs more massive than 10 times Jupiter's mass, they are able to very briefly fuse deuterium into helium. Deuterium is sometimes called heavy hydrogen; it is a form of hydrogen in which the nucleus already includes 1 neutron in addition to the solitary proton of ordinary hydrogen.

- By adding 1 proton, the deuterium becomes a "light helium," having 2 protons and 1 neutron instead of the usual 2 plus 2. This "light fusion" process does provide a bit of energy to the brown dwarf. It's only for a brief time of perhaps 100 million years or so, but it does serve as another characteristic that distinguishes brown dwarfs from planets.

- In fact, the fusion process—or the lack thereof—serves as one of our most direct methods for confirming the existence of brown dwarfs. This is important, because at first blush, many brown dwarfs can appear so similar to very low-mass stars that for decades the hunt for brown dwarfs was stymied by the uncanny resemblance. After all, the lowest-mass stars, weighing in at a mere 8% of the mass of the Sun, are red and faint, just like brown dwarfs.

- Despite the name, brown dwarfs are not brown. To the eye and to a telescope's camera, they appear deep red or magenta in color—the same as the lowest-mass stars, which we call red dwarfs.

The Physical Nature of Brown Dwarfs

- How can we distinguish a brown dwarf (a failed star) from a red dwarf (a small but legitimate star) if they both appear more or less the same in their actual colors? This is where the power of dissecting the light spectrum comes to the rescue. In particular, the presence of the element lithium in an object's atmosphere is a very strong confirmation that it is too low in mass to be a star. Most stars are born with a certain amount of lithium, inherited from the clouds of gas and dust from which they are formed.

- Lithium turns out to be a very fragile element, at least as far as nuclear reactions are concerned. Even at relatively low temperatures, and well before most stars ignite full-on hydrogen fusion, they are able to fuse lithium into beryllium. Consequently, true stars, as they are completing their birth process and certainly by the time they start their middle lives as main sequence stars, have already burned up all of their lithium.

- It was realized early in the search for brown dwarfs that an object with a mass lower than that of a true star will not become warm enough to fuse lithium. So, if we see the spectral signature of lithium in a star, that tells us that it is not a star but, rather, an object that never became hot enough in its interior to fuse one of the easiest elements of all. Therefore, it must be a brown dwarf.

- In ordinary stars, the lower in mass, the dimmer the luminosity and the cooler the temperature, so the redder the color. In other words, with ordinary stars, the dimmest stars are the reddest ones. However, the opposite is true for brown dwarfs.

- The reason for the strange and counterintuitive colors of brown dwarfs has to do with the fact that these objects are so cold that instead of having atoms in their atmospheres, their atmospheres are dominated by cold molecules, such as methane, ammonia, and even water vapor. These molecules absorb so much of the reddest wavelengths of light that the brown dwarf ends up appearing blue. In fact, the coolest known brown dwarfs are among the bluest.

- Amazingly, these very cool brown dwarfs have temperatures comparable to our own bodies at room temperature—about 300 degrees Kelvin. And because they are so cool and dim, most of the known brown dwarfs are very close by. Indeed, some of the closest known objects to us are brown dwarfs, the nearest of which is only 6 light-years away.

- An important clue to the physical nature of brown dwarfs comes from examining their physical sizes in comparison to their masses. There is a direct relationship between the mass of a star and its size—more massive stars are bigger—and this relationship continues all the way down to even planets like Jupiter. However, brown dwarfs, despite having masses that place them above planets like Jupiter, are actually smaller than Jupiter.

- Just like white dwarfs and neutron stars, brown dwarfs are dead stars that hold themselves up against gravity using degeneracy pressure, which uses the strange properties of quantum mechanics to generate pressure by compressing the particles ever more tightly.

- But how do we know the sizes of brown dwarfs? How do we know the relationships between their basic properties? Stars that are parts of eclipsing binary systems are among our most important informants of the properties of stars. Eclipsing binary systems are pairs of stars that periodically pass directly in front of one another, eclipsing one another, and from those mutual eclipses, we can measure things like the sizes of the stars.

- Unfortunately, there is at this time only one known example of an eclipsing binary system in which both siblings are brown dwarfs. So, that one system serves as a kind of Rosetta stone for understanding the properties of brown dwarfs more generally. From that system, in the stellar nursery in Orion, we have been able to directly measure the properties of the two brown dwarfs in the system. Moreover, because the system is in a stellar nursery, it gives us a glimpse into the process by which stars are stillborn.

The Formation of Brown Dwarfs

- Brown dwarfs are something between star and planet but are neither. Their masses are in between those of planets and stars, but what does their birth process—or stillbirth process—look like? Do they form like stars, collapsing under gravity and attempting but failing to ignite fusion, or do they form like planets, in the disks of gas and dust in orbit about stars?

- This was a basic question that persisted for some time. However, the evidence now appears to be quite incontrovertibly in favor of the starlike formation scenario. There are several lines of evidence for this interpretation.

- First, we now have exemplars of brown dwarfs in stellar nurseries that are ringed by disks of gas and dust all their own. Such cases demonstrate that brown dwarfs undergo a gravitational collapse very much like that which stars experience as they form.

- A second piece of evidence is that we now have exemplars of brown dwarfs with actual planets orbiting them. This makes sense given that we've seen brown dwarfs ringed by disks of gas and dust. But the discovery of planets around brown dwarfs lends further support to the idea that brown dwarfs form like stars. It further indicates that failed stars in some cases also represent failed solar systems.

- Why does nature sometimes decide to abort the stellar birth process and produce a stillborn brown dwarf instead? It appears that the dynamics of the star-formation process itself may be at fault. Interactions between forming sibling stars can lead to ejections of some stars, kicking them out not only from the sibling family, but in some cases from the stellar nursery altogether.

- A currently favored explanation for why some stars may fail to fully form is that this dynamical ejection process cuts some protostars off from the reservoir of material that they would otherwise have fed from. Because they can't feed from this reservoir, they are unable to build up enough mass to become full-fledged stars. In this sense,

brown dwarfs really represent aborted stars as opposed to stillborn stars, having been forcibly removed from the womb that would have presumably otherwise nurtured them to full term and to status as a full-fledged star.

- Regardless of the cause of a brown dwarf's existence, what is undeniable is its ultimate fate. A brown dwarf, unable to generate its own light and heat through fusion, will fade over time, becoming ever cooler and dimmer, eventually fading entirely from view.

- But in the meantime, as long as we can see and study them, these stillborn stars provide us our most important and direct way of understanding the stellar birth process. By studying brown dwarfs, we gain insight into the circumstances under which some stars ignite while others fail to form at all.

Suggested Reading

Boss, *International Astronomical Union Working Group on Extrasolar Planets Definition of a 'Planet.'*

Burgasser, "Brown Dwarfs."

Questions to Consider

1. In light of how they come to be formed, are brown dwarfs best thought of as stillborn stars or as aborted stars?

2. What role does gravity, which normally drives the stellar birth process, play in the failure of brown dwarfs to become full-fledged stars?

The Dark Mystery of the First Stars

Lecture 20

In this lecture, you will learn about the biggest, most massive stars that might have populated the universe's very beginnings and that would have initiated the stellar life cycle for the rest of time. There are multiple good lines of evidence that such a strange population of stellar beasts roamed the early universe. To understand those first ancestral stars, we might ultimately have to penetrate the hidden nature of the strange dark matter particles that still fill the universe, whose gravity we can sense but which we have not even seen with our own eyes.

The Oldest Stars in Our Galaxy

- For decades, astronomers have worked in an ongoing effort to find the truly oldest stars in our galaxy because we can use them to directly measure what the chemical composition of the universe was like at the time that our galaxy formed 12 to 14 billion years ago, soon after the big bang.

- But searching for the oldest relic stars in our galaxy is challenging because there is not much about a star that, on the face of it, gives us a hint that it is much older than any of the other billions of stars swarming around the galaxy.

- To find the oldest stars, we first have to restrict our attention to relatively low-mass stars—because the lowest-mass stars live the longest. If a star like our Sun formed when the galaxy was very young, it would already have ended its life, because stars like our Sun live to be about 10 billion years old, whereas the galaxy is more like 14 billion years old. In contrast, virtually every star ever born weighing less than about 80% of the Sun's mass is still around, because such low-mass stars live longer than the galaxy is old.

- The problem is that such low-mass stars constitute about 75% of all stars in the galaxy, and the galaxy has been birthing such stars

continuously since it began. So, we're talking about roughly 150 billion of these low-mass stars. In addition, those 150 billion low-mass stars all look pretty much the same, because they are all still main sequence stars. They have similar temperatures and colors and luminosities. The answer is to look for a star that's jumping out at you and then use the light spectrum of that star to verify that it has little to no heavy elements in its makeup.

- The oldest stars in our galaxy were born at a time in the galaxy's history when the galaxy as a whole had a much less orderly shape. Before the flattened disk of the Milky Way formed through gravitational collapse, our galaxy had a more nearly spherical shape. So, the stars that were born then moved through the galaxy in a more disorderly spherical swarm about the center of the galaxy, in contrast to the more orderly circular rotation of stars like our Sun in the disk of the Milky Way today.

- Those early stars that are still around today continue to orbit the galaxy in that spherically distributed, more haphazard fashion, making up what we call the halo of our galaxy, extending to large distances all around it. And because they orbit the galaxy in that way, they periodically plunge down through the disk of the galaxy to the other side and then eventually plunge back up through the disk, over and over through the eons.

- As a result of this, some of the nearest stars to the Sun right now happen to be these very old halo stars that are nearby—not because they are true neighbors of our solar system residing in the disk of the galaxy, but because they are interlopers plunging rapidly through the disk on their way to the other side.

- These stars turn out to be relatively easy to spot because we can see them tearing by us. And they tear by in a very peculiar direction—straight up or down instead of along the direction of motion of our Sun and of other stars in our neighborhood.

The Methuselah Star

- The star that currently holds the record as the oldest star in our galaxy is called HD 140283, or the Methuselah star. It's a fairly unremarkable star, but it was recognized about 100 years ago because of its remarkably fast and odd direction of motion. It is moving at 800,000 miles per hour, which is so fast that the Hubble Space Telescope could measure its motion in the sky over the course of just a few hours. It is also very bright, because it just so happens to be plunging through the disk of our galaxy very close to the Sun's position in the disk.

- The latest measurements using the Hubble Space Telescope have allowed astronomers to precisely pinpoint the star's distance—190.1 light-years—which in turn has permitted its luminosity to be accurately measured from its apparent brightness. That luminosity, together with its color or temperature, lets us use the Hertzsprung–Russell diagram to measure exactly where the star lies in relation to the main sequence.

- This star is just entering the final stages of its life, leaving the main sequence stage and turning into a red giant. Therefore, by placing it accurately in the H–R Diagram, it is possible to determine its age: 14.5 billion years, plus or minus 0.8 billion years. With the age of our universe being 13.8 billion years, the measurement of Methuselah's age puts it right at the maximum possible age for a star in our universe, meaning that this star must have formed just as the galaxy itself was forming and very soon after the big bang.

- From careful measurements of the elemental signatures in its light spectrum, scientists have determined that Methuselah contains just a smidgen of heavy elements, a mere $1/250^{th}$ of the amount contained in the Sun—but that's more than zero. And this tells us definitively that there must have been a generation of stars that came even before Methuselah and its cohort to create that smidgen of heavy elements for Methuselah to inherit.

- Any such prior generation of stars would have had to exist sometime after the big bang; they could not have existed prior to the start of the universe as a whole. So, with Methuselah's age having been pinned to be at least 13.7 billion years old, and the universe having begun 13.8 billion years ago, there is a tiny window of time—about 0.1 billion, or 100 million years—during which time a generation of pre-Methuselah stars could have existed.

- In addition, the measurements of Methuselah's detailed elemental abundances tell us that there is something peculiar about this star's chemical makeup: It has much more oxygen relative to its hydrogen than what we currently see in the universe's mix of chemical elements.

Dark Stars

- Because none of the first stars that formed in the universe are around anymore, it is not possible to directly observe them. So, the only way to understand what they must have been like is through detailed calculations and computer simulations. And until recently, such simulations couldn't be done because of the sheer computing power required.

- You might think that the stellar birth process at the beginning of the universe would be simpler than it is today because the universe soon after the big bang was a lot less complex than it is now. Almost all of the matter in the universe was in the simplest form possible—simple hydrogen and helium gas. There were no heavier elements, and there were no dust particles. And there were no existing stars with their magnetic fields and stellar winds to complicate things.

- The complication is that in the early universe, the ordinary matter with which we are familiar—stuff like hydrogen gas—was not the form of matter that controlled things, gravitationally speaking. The dominant form of matter was what we call dark matter, a mysterious form of matter that exerts the same gravity as ordinary matter but whose physical properties we are only beginning to understand.

- Current estimates are that dark matter actually comprises 90% of the total matter content of the universe and would have also dominated the matter content of the universe back when the very first stars were forming.

- So, at the universe's beginning, from the standpoint of gravity and its influence in the formation of the first stars, imagine the universe as a place principally filled with dark matter. Regions where the dark matter was denser were the places where the ordinary matter out of which stars form—hydrogen and helium in the young universe—collected. In addition to the nature of dark matter still being largely unknown, these regions of denser dark matter would have been enormous, further exacerbating the challenge of simulating these regions computationally.

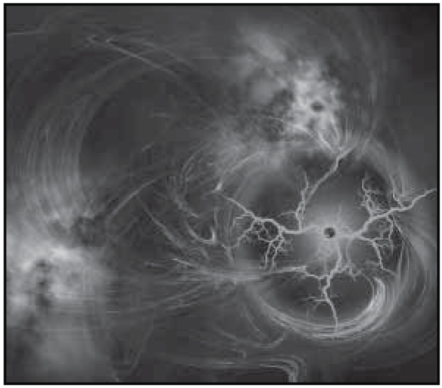
- In recent years, however, advances in computational power have made it possible for scientists to simulate the formation of the earliest stars, and the simulations tell us that the masses of stars formed in the dense dark matter regions of the early universe would have been about 100 to 300 times as massive as the Sun—an extraordinary amount of mass for a star.

- This idea remains controversial. In fact, the most recent simulations indicate that the first stars might have been less hefty, around 40 times the mass of the Sun. The consensus is that the very first stars in the early universe must have been much more massive than the stars that we observe forming today. There is also an emerging consensus among astronomers that there must have been at least some first stars that were more massive than 140 times the mass of the Sun.

- A number of astronomers are becoming convinced that some of the first gargantuan stars may have been made not of ordinary matter, but mainly out of dark matter. If correct, then the first stars to form in the early universe would have been what some are calling dark stars, fueled by an altogether different engine than stars as we know them today.

- Ordinary stars like the Sun today shine because they are fueled by nuclear fusion in their core that converts hydrogen to helium. But these theoretical dark stars would have run on dark matter particles colliding and annihilating each other.

- Dark matter is a substance that astronomers have not yet observed directly—that's why we call it "dark"—but we infer its existence because we can measure its gravitational effects on visible matter. We don't yet know exactly what dark matter is, but it must be some type of elementary particle that we have not yet observed in particle colliders.



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Dark matter, a mysterious substance, makes up 26.5% of the matter-energy composition of the universe.

- The findings of this area of research so far suggest a dramatic altering of the theoretical framework for the formation of the first stars. Dark stars are an entirely new kind of star from anything we've known or conceived of before.

- According to dark stars theory, the first stars are thought to have formed inside clouds of dark matter, when hydrogen and helium gases cooled to a temperature at which nuclear fusion could begin. In more conventional theories of the first stars, dark matter doesn't affect this process except to provide the gravity to bring the gases together.

- However, in dark stars theory, the dark matter concentrations are high enough for the particles in the dark matter clouds to collide

with and annihilate each other, destroying themselves and, more importantly, providing a source of internal heat to support the very massive star without relying on nuclear fusion alone.

- As a result, the star can be enormous—perhaps as large 2000 times the size of the Earth's orbit about the Sun. And when these enormous stars finally end their lives as supernovae, perhaps as quickly as 1000 years or even less after they formed, they leave behind the heavier elements such as carbon, nitrogen, and oxygen that became part of the next generation of stars, such as in the Methuselah stars still roaming our galaxy.

Suggested Reading

Larson and Bromm, "The First Stars in the Universe."

Nicolson, *Dark Side of the Universe*.

Questions to Consider

1. In what ways do the very first generation of stars differ from the "ordinary" stars that populate the universe today?

2. Why doesn't dark matter play as much of a crucial role in the lives and deaths of stars now as it did in the very early universe?

Stars as Magnets

Lecture 21

In this lecture, you will continue to explore the cutting edge of current research into the nature of stars. In particular, you will explore the phenomenon of magnetism in stars. Many of the extreme behaviors of stars can be understood through their magnetic nature. As you will learn, through their spins, stars can act as powerful magnets, affecting not only themselves but also the space around them. In a sense, it is through its magnetism that a star is able to extend its influence far beyond its surface.

Magnetism

- One of the basic properties of magnetism in nature is that magnets never occur with single poles, or monopoles. A basic magnet, whatever it's made of or however its magnetism is generated, has two poles—a north pole and a south pole. It is dipolar.

- Stars like the Sun also have dipolar magnetic fields. There is a point typically near the north rotational pole of the star that is the north magnetic pole and a point typically near the south rotational pole that is the south magnetic pole.

- How do stars, which are gaseous fluids, generate and sustain their magnetic fields? The basic answer is electricity, and the intimate relationship between electricity and magnetism.

- Up until the 19th century, electricity and magnetism were thought to be independent forces, but ever since James Clerk Maxwell devised the laws of electromagnetism, we understand that they are in fact manifestations of a unified force. One of the consequences of that fact is that magnetism and electricity can induce one another.

- For example, in an electromagnet, a strong electrical current is used to create a magnetic field. The way this works is based on one of Maxwell's laws, which states that electrically charged particles

moving around in a current produce a magnetic field. The magnetic field produced by an electrical current is oriented perpendicular to the motion of the current. That's precisely what happens within a star—a star is an electromagnet.

- The gas within a star is hot and so is partially or fully ionized. And all stars rotate, or spin. The charged particles within a star, carried along by the star's rotation, constitute an electrical current, and as such, they generate a magnetic field.

- As the star's rotation carries the current around parallel to the star's equator, the magnetic field it generates is oriented perpendicular to the equator, so the poles of the magnetic field are oriented such that the north and south magnetic poles correspond closely to the rotational axis of the star.

- A magnetic field is really just a way of representing the ability of a magnet to act at a distance. Another important aspect of magnetic field lines is that only charged particles feel them; electrically neutral particles don't notice magnetic field lines. A charged particle in the presence of a magnetic field is forced to move along that field line—up or down along it—and cannot move across it. When charged particles, such as electrons, encounter a magnetic field, they slide effortlessly along the magnetic field lines, like beads on a string.

- The Sun is a magnet. The Sun rotates—its period of rotation is about 26 days—and that equatorial rotation represents an electric current that in turn generates a magnetic field emanating from the Sun's poles. The Sun's global magnetic field lines can be visualized as a mesh of tendrils, like hair, that grow out of the north magnetic pole and wrap down around the Sun, then reconnect with the Sun's surface down at the south magnetic pole.

- However, there are two important ways in which the detailed topology of the Sun's magnetic field differs from this simple representation. The Sun's rotation—the same rotation that causes

the Sun’s magnetic field in the first place—also shapes and distorts the magnetic field in two important ways.

- The first effect is that the magnetic field gets wrapped around the equator and balloons out at the poles. This makes the magnetic field at the equator tend to be tightly confined near the Sun’s surface, whereas at the poles it extends far, far away from the Sun’s surface. In other words, near the equator, the magnetic field is tightly wound and even kinked up, whereas near the poles it is straight and stiff.

- The second way in which the Sun’s rotation alters the Sun’s magnetic field has to do with that tight wrapping near the equator. As the magnetic field near the equator becomes more and more wrapped, then it becomes kinked and pokes up out of the Sun’s surface. The places where those kinked loops poke up and back into the surface are the places where pairs of sunspots form.

- For those kinked loops protruding from the Sun’s surface near the equator, hot ionized gas lifts up along those field lines and is held aloft by the magnetic field, creating amazing solar prominences. These prominences can erupt as energetic flares, driving so-called space weather. As for the straight magnetic field lines emanating from the Sun’s poles, charged particles flow along those lines way out from the Sun. This is the solar wind.

- The solar wind has an important influence on the Sun. As particles from the Sun’s rotating surface stream along the magnetic field, they end up flung out into the outer reaches of our solar system. These solar wind particles take a tiny, insignificant bit of the Sun’s mass with them. But these particles also take with them a bit of the Sun’s spin energy—a bit of its angular momentum.

- The resulting steady decrease of the Sun’s angular momentum leads to a steady slowing down of the Sun’s spin. In fact, 90% of the Sun’s original spin has already been lost, and over the remaining course of the Sun’s life, it will continue to wind down, probably spinning at only half of its current speed by the time it’s done. And

as it winds down, its magnetism will steadily decrease, meaning less severe solar storms at Earth.

The Internal Structures of Stars

- Interestingly, stars more massive than about 3 times the Sun's mass generally possess extremely weak magnetic fields. This is surprising because more massive stars tend to be more luminous, more voluminous, and hotter. But there is an important way in which massive stars are deficient in comparison to lower-mass stars, and this difference provides an insight into the real mechanism for the generation of magnetic fields in stars. In short, it has to do with the internal structure of stars.

- One of the key features of the Sun's internal structure is that the outer layers of the Sun form the so-called convective zone, in which the energy from the Sun's core is transported upward to the surface through the roiling circulatory motion, similar to that of a boiling pot of water. Stars less massive than the Sun have an even more substantial outer convective zone relative to their overall size. In contrast, stars more massive than the Sun have very thin outer convective zones, and the most massive stars have no outer convective zone.

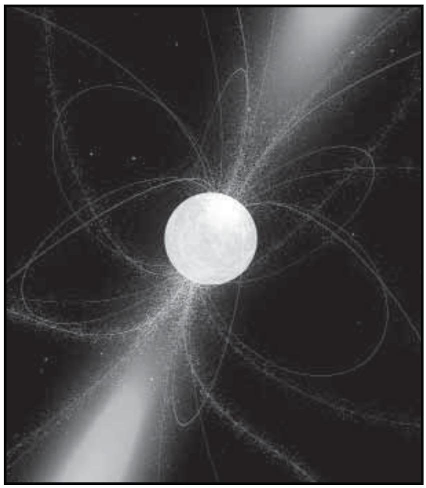
- Therefore, the presence of an outer convective zone, and its depth relative to the overall size of the star, is an important ingredient in the generation of a magnetic field. Fundamentally, the convection is responsible for the generation of the electrical currents that are necessary, together with the star's rotation, to create the star's magnetic field. That process of combining convective currents with rotation to create a magnetic field is called a dynamo.

- Have you ever used a device that powers a light or a radio by turning a crank? That's a dynamo, although working in reverse. In this type of dynamo, a magnet is used to generate an electrical current by spinning a loop of wire around that magnet. In a star, it's the same idea—only the electrical current formed by the convection zone is spun around by the star's rotation, and this creates a magnet.

- This relationship between a star's internal structure—in particular, the depth of its outer convection zone—and the strength of its magnetic field also explains the pattern of flaring of X-ray emission that we observe in other stars.

- Perhaps counterintuitively, the stars with the strongest magnetic flares and the most intense bursts of X-ray emission are the lowest-mass stars. But this makes perfect sense, because the lowest-mass stars are also the ones with the deepest convective zones and, therefore, have the strongest dynamos with which to generate the strongest magnetic fields.

- As a consequence of this, massive stars tend to be rapidly spinning—and tend to remain so throughout their lives. Without a strong magnetic field to drive a wind to remove angular momentum, they cannot slow down. On the other hand, less massive stars do slow down with time, just like the Sun. This effect has led to the development of a promising technique, called gyrochronology, for inferring the ages of stars from their spins.



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Pulsars were initially discovered because they emanate regular pulses of radio waves.

Pulsars

- The role of magnetism in the birth of stars remains one of the frontiers of research. But magnetic fields matter at the ends of stars' lives, too. Indeed, some of the most extreme phenomena we have observed from stars are from the highly magnetized corpses of dead stars. The best example of this is what we refer to as pulsars.

- Pulsars are neutron stars. But they are neutron stars that we happen to view from Earth at just the right angle so that the intense light they emit from their extremely strong magnetic poles aims right at us as the neutron star spins around. This occurs because the magnetic poles are offset somewhat relative to the spin axis of the neutron star, so the magnetic poles swing around as the neutron star spins.

- One of the first pulsars to be discovered was the neutron star at the center of the Crab Nebula supernova remnant. That pulsar spins about 30 times per second, and in fact, that pulse can even be seen in visible light. But most pulsars radiate their pulse beams primarily in radio light.

- The first pulsar ever discovered came about 30 years after the invention of radio telescopes. Since then, many pulsars have been discovered, and they all spin very fast. The slowest among them spins about once per second, and the fastest—known as the millisecond pulsars—spin about 1000 times per second.

- The regularity of a pulsar's pulse is so perfect that it can be used as one of the most exact timekeeping devices known. As a result of this exquisite timekeeping ability, pulsars have been used to prove Einstein's prediction of gravitational radiation, in which a pair of pulsars orbit one another so fast that they radiate away gravitational energy and are spiraling into one another.

- The pulsar regularity also led to the discovery of the first exoplanet. The first planets discovered outside of our own solar system were discovered not around another living star, but around a pulsar.

Suggested Reading

Choi, "Alien Planets Circling Pulsing Stars May Leave Electric Trails."

McNamara, *Clocks in the Sky*.

Questions to Consider

1. What does the existence of pulsars imply for how we might modify our strategy to detect true signals from another civilization?

2. What would a civilization on a planet orbiting a pulsar have experienced in the lead-up to the star having become a neutron star? Could such a civilization have survived and still live on the pulsar planet?

Solar Storms—The Perils of Life with a Star

Lecture 22

In this lecture, you will learn that the Sun governs the space weather of its environs and, in turn, exerts a direct influence over weather on Earth, the health of our astronauts in space, and the durability of the satellite platforms upon which our technologically built world increasingly depends. However, although the Sun's weathering of our planet might seem harsh now, it is nothing compared to the intense weathering that the Sun exerted on the proto-Earth, a weathering that might have been an important part of how the building blocks for life as we know it came to be.

Aurorae

- One of the most basic—and beautiful—manifestations of space weather on Earth is the aurorae. The word "aurora" derives from the Latin word for dawn. Aurorae are the eerie curtain-like sheets and long streamers of shimmering light that appear near the north and south poles. These wonderful, if strange, apparitions have been noticed by people going all the way back to the most ancient civilizations, particularly those who resided at far northern latitudes.

- The aurora borealis occurs above the north pole, and its counterpart, the aurora australis, occurs above the south pole. But with no early civilizations living near Antarctica, only the northern lights (as the aurora borealis is also known) were recorded in ancient times. It was noticed early on that the northern lights did not occur constantly but, rather, sporadically. And when they occur, they tend to occur strongly, like a gust or storm.

- Today, our basic picture for how the aurorae are produced is as follows. Energetic flares erupt on the Sun's surface, driven by the twisting and kinking of the Sun's magnetic field. Those flares, representing the sudden snap of the Sun's kinked magnetic field and signaled by a burst of X-ray light, fling a strong gust of energetic, charged particles away from the Sun and into interplanetary space.

Most often, these so-called coronal mass ejections and the solar energetic particles that they carry are launched by the Sun in a direction other than toward Earth.

- But in some cases, by chance, the solar energetic particles are directed at Earth. After a short travel time from the Sun to Earth, those particles impact the Earth's magnetic field—which is good news for us because these particles, which would otherwise directly impinge on the Earth's surface and cause biological damage, are instead deflected.

- A charged particle in the presence of a magnetic field cannot move across a magnetic field but can effortlessly move along a magnetic field line, like a bead on a string. So, the incoming solar particles ram into the Earth's magnetic field and then free-fall slide along the magnetic field toward the two points from which the Earth's magnetic field emanates—the north and south poles.

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The aurora borealis is found in the Northern Hemisphere of Earth.

- This is where we see the aurorae, as those energetic particles, sliding along the Earth's magnetic field, at last impinge on the Earth's atmosphere, heating it, and causing the atoms in the air to fluoresce. The same basic process occurs on the other planets in our solar system, too.

- Earth's magnetic field provides some protection from otherwise damaging energetic radiation. However, for astronauts in space, such gusts of space weather pose a very real danger. For example, the class of very energetic solar flares that occur approximately once per year would cause a level of radiation poisoning to an astronaut on the Moon sufficient to cause death. Even airlines monitor the occurrence of such solar storms in order to modify flight plans to protect their crews if needed.

Impacts of Solar Storms

- One of the most extensively studied impacts of solar storms on biological life is how they affect the navigational abilities of some animals. For example, homing pigeons have been shown to have their navigational abilities disrupted, as have dolphins and potentially whales as well.

- It has been suggested that this may be caused by minerals in the animals' heads or beaks being triggered by geomagnetic currents generated by the solar storm. However, more recent research suggests that the sensory effect is caused by some other mechanism that has yet to be identified.

- Another major impact is on our communications systems, which increasingly rely on satellites in Earth's orbit to relay and transmit long-distance and cellular signals. Direct damage to the electronics aboard these satellites is an obvious concern.

- Another concern is the effect of the changing height of the Earth's atmosphere. When a strong shower of solar energetic particles strikes the Earth's atmosphere, those energetic particles deposit their energy into the atmosphere, which has the effect of puffing

it out a bit. This puffing of the atmosphere increases the amount of drag on the atmosphere that low-altitude communications satellites experience, which can cause them to prematurely spiral in to the atmosphere and begin to burn up.

- The effect of space weather on satellites that we increasingly rely on for navigation—such as GPS satellites—has understandably become a major concern. During particularly severe solar storms, positions from GPS satellites have been known to be off by as much as a few miles.

- If electrical disruptions of telecommunications satellites seem bad, consider what such disturbances might do to an electrical power grid on the ground. Indeed, among the biggest ongoing concerns highlighted in recent research reports is the potential for significant negative impact on major metropolitan electrical distribution systems.

- The Earth's magnetic field moves in response to the impact of energetic particles from a solar storm, and that motion of the Earth's magnetic field generates electricity in any electric circuits that might be present nearby.

- So, those large electric circuits on the ground—our electric grid—have strong electric currents induced in them by the Earth's magnetic field moving in response to the solar storm. These induced currents can be quite strong and, most importantly, can spike unexpectedly.

- Similar concerns apply to the major pipelines that move petroleum across vast stretches. These pipelines, while of course not intended as electrical circuits, can have electrical currents induced in them in the same way that circuits in the electrical grid can. And because these pipelines were never intended to carry electricity, there generally has not been the same degree of safety mechanisms built in.

- Because of all of these concerns, there are now major research efforts underway to improve our ability to predict bad space weather. For example, the National Science Foundation's Center for Integrated Space Weather Modeling led by Boston University has been developing sophisticated computer models that are now being implemented by the National Weather Service.

Chondrules in Meteorites

- Stars do more weathering of their environs when they are young. From X-ray studies of young stars, we now know that the Sun, when it was young, produced 10,000 times harsher space weather than it does now.

- In addition to the extreme weathering driven by powerful gusts from the Sun, there is good evidence that the young Earth was subjected to powerful electrical disturbances directly from the Sun's magnetic field. A number of the meteorites that have been found include clear evidence of having been subjected to lightning that penetrated deep into their interiors even before they encountered any effects of falling through the Earth's atmosphere.

- The evidence for this is the presence of so-called chondrules within the meteorite—small nodules of rock embedded within the meteorite that indicate a portion of the meteorite was flash heated, melting it. Then, it resolidified within the meteorite as distinct chondrule inclusions.

- How would that happen? A young star's magnetic field can dig into its surrounding protoplanetary disk and channel material from the disk onto the star. That same magnetic connection between the star and its disk can channel highly energetic particles from the young star into the disk and onto any small rocky bodies that may be beginning to coalesce into planets.

- As these energetic particles from the young star stream onto these rocks—future meteorites—there can be electrical discharges around and on these rocks. Such electrical discharges are a form

of lightning, so this would explain the features that we see in some meteorites that have fallen to Earth with signatures of having been exposed to a kind of lightning in the very distant past, when the solar system and the Earth were first forming.

- Clearly, the proto-Earth was in an extremely hostile environment, at least as far as life as we know it now would be concerned. But that doesn't mean that it was necessarily a bad thing then. In fact, it may have been crucially important to the very emergence of life on Earth.

- The class of meteorites known as carbonaceous chondrites are among the most pristine examples known of the material that comprised the environs of the Sun's protoplanetary disk, within which the Earth was formed. Embedded within these meteorites are various types of organic material.

- For example, more than 70 different amino acids, the building blocks of proteins, have been identified. Laboratory experiments dating back to the 1950s have shown that zapping basic organic compounds with high-energy particles or with lightning can synthesize such amino acids.

- In fact, more recent lab experiments have shown that it is possible for lightning or high-energy X-rays from space weather to stimulate the creation of adenine, which is one of the four types of bases that make up DNA and the genetic code to all of life.

- Ideas have been proposed for harnessing the Sun's weather as a means of propulsion for future space flight. The idea here is to build spaceships that have enormous sails made of Mylar or some other strong but lightweight material. These sails would be pushed by the gusts of wind of particles streaming from the Sun, and the gustier the better as far as getting more propulsion is concerned.

Suggested Reading

Moldwin, *An Introduction to Space Weather*.

Schopf, *Life's Origin*.

Questions to Consider

1. What are the most important ways in which the Sun affects life on Earth, both now and when the Earth was very young?

2. How might space weather potentially help counteract the effects of human-caused climate change? How might it exacerbate the problem?

The Stellar Recipe of Life

Lecture 23

What is the recipe of life? The most important ingredients—the flour, salt, baking powder, and yeast—are carbon, nitrogen, oxygen, and hydrogen. From our pantry, we also need a handful of other ingredients in smaller amounts, but these are nonetheless crucial to the success of the recipe: calcium, sodium, sulfur, chlorine, phosphorus, potassium, and iron. Finally, we need the spice rack—smidgens of trace elements that are the spice of life. These elements are copper, zinc, selenium, and cobalt.

The Main Ingredients

- Imagine that we are cosmic chefs and that the recipe we're preparing is the recipe of life. What ingredients does the recipe call for? In our pantry, we have the major elements, and in our spice rack, we have the trace elements. Our kitchen is the galaxy, with tools such as blenders in the form of supernovae that stir up the batter. Our oven is a star. And gravity is the cake form, holding the ingredients together while they bake.

- The ingredients that we would mainly require are hydrogen, carbon, nitrogen, oxygen, calcium, sodium, sulfur, chlorine, phosphorus, potassium, and iron. These elements make up almost everything around us and are the bulk elements of our bodies. Sure enough, aside from hydrogen provided by the creation of the universe itself, these are the elements that stars "cook" during their lives.

- All living things on Earth have just 4 elements in common: carbon, nitrogen, oxygen, and the hydrogen that bonds to them. Ignoring helium, those 4 elements are the 4 most abundant elements in the universe. Hydrogen is about 75% of all matter, a direct inheritance from the big bang.

- Carbon is made by all stars, including massive stars as one stage of fusion, and by lower-mass stars as the final stage of fusion before their deaths. So, no wonder it's so abundant. It's the one element, helium aside, that every star in the universe will manufacture. Carbon is the flour in our pantry, so it makes sense that just about anything we might bake will not only involve it, but also use it as a base ingredient.

- Nitrogen and oxygen are the first elements after carbon to be fused by massive stars, and they are also the elements that, after carbon, provide stars with the most oomph in the form of additional fusion energy. So, it's not surprising that these are the next most abundant elements in the universe. These are the sugar and salt in our pantry, and it's no wonder that anything we might bake will include these ingredients also in good measure.

Other Crucial Ingredients

- Next in our pantry are the elements calcium, sodium, sulfur, chlorine, phosphorus, potassium, and iron. Calcium is an essential component in human bones and teeth. So, if you're going to cook up a recipe of life, calcium is the natural choice as a leavening agent. Every atom of calcium was produced in massive stars through the fusion of sulfur and 2 helium atoms.

- We immediately associate sodium with salt, so let's think of it as the salt in our cosmic pantry. This is an ingredient that we're definitely going to need as a foundation for the flavor of our recipe for life, but we don't want to overdo it. Every atom of sodium in the universe was made in high-mass stars through the fusion of 2 carbon atoms. In our bodies, sodium is an essential nutrient that regulates blood volume, blood pressure, fluid equilibrium, and pH balance.

- Phosphorus is, after calcium, the next most abundant element in the human body. Most of it is just locked up in our bones and teeth, where it helps form the protective enamel layer, but a tiny bit of it is so essential that life as we know it simply would not exist or function without it. This is the baking soda in our cosmic pantry.

- Phosphorus is required by all known forms of life. It plays a major role in biological molecules like DNA and RNA, forming a part of their structural backbone. Importantly, phosphorus is also the key component of adenine triphosphate, or ATP, in which a group of 3 phosphorus atoms provide the molecule's key features and functions. Nearly every cellular process that uses energy obtains it in the form of ATP. Every atom of phosphorus that exists was made in massive stars through the fusion of silicon and helium.

- Potassium is the next most abundant element in the body. Massive stars make potassium through the fusion of 2 oxygen atoms; every atom of potassium in the universe was made this way. In our bodies, potassium is crucial for proper nerve transmission. Without enough potassium, fingers freeze up and, eventually, cardiac arrest follows because the heart's beating function is regulated by this important element.

- Sulfur is made in massive stars through the fusion of silicon and helium. Because of its nasty smell, it has throughout history been associated with hell-fire burning. However, we cannot live without it. Sulfur is an essential component of all living cells. It is present in all proteins and enzymes that contain certain essential amino acids.

- Pure chlorine gas is about as horrific a poisonous substance as you could imagine. A whiff of pure chlorine gas is like a blast of a blowtorch to the sinuses and lungs, and breathing more than just a small amount can cause instant death. But together with sodium, chlorine forms regular table salt. And in our bodies, chlorine serves an important role in nerve signaling and digestion.

- Iron is the heaviest element that massive stars produce before they explode as supernovae. Every atom of iron in the universe was smelted in the crucibles that are the cores of massive stars in the final, dying gasps of their lives. Iron atoms—sprinkled through the galaxy by supernova explosions spreading these dead stars' material up through galactic geysers and across the galaxy—are stellar ashes

which make up our lifeblood as well as the most massive and substantial products of human ingenuity.

The Spice Rack

- If we've just gone through the pantry of our cosmic kitchen, representing the most important and foundational ingredients of life, we'll also want to make sure that we have the right spices in our spice rack. These are the trace materials that, used in pinches, make up a tiny but nonetheless crucial part of the overall recipe.

- Indeed, life depends on smidgens of certain rare elements: copper, zinc, selenium, cobalt. These elements show up in our hair and blood. These are the elements that stars forge in their fiery deaths.

- The first element in our spice rack is copper. In our bodies, just a trace amount of the stuff—about 2 parts per million—is crucial for proper iron uptake. And because iron is so important in our blood, copper deficiency can in turn lead to anemia-like symptoms, bone abnormalities, osteoporosis, and impaired metabolism.

- Another essential trace element in all animals is zinc, which is a component of hundreds of different enzymes. There are just a few grams of zinc distributed throughout the adult human body. Most of it is found in the brain, muscles, bones, kidney, and liver, with the highest concentrations in the prostate. There may be no other element produced in the fiery supernova deaths of stars that is so intimately connected with the conception of new human life.

- In addition to copper and zinc, the element cobalt is essential to all animals. It is a key constituent of cobalamin, also known as vitamin B12, which is essential to the health of our nervous system. It is made by bacteria in the guts of ruminant animals, which convert cobalt-based salts into B12.

- The final element in our metaphorical spice rack is selenium, which makes up less than 0.01% of our body mass but plays an important

role in the functioning of the thyroid gland and in every cell that uses thyroid hormones.

Stocking Our Cosmic Kitchen

- Where do we get the ingredients for our cosmic pantry and spice rack? Hydrogen is essentially free, having been provided by the big bang. However, every bit of carbon requires a star to make it. Stars like our Sun make it as red giants shortly before their deaths. And nitrogen and oxygen require massive stars to fuse them from carbon and helium atoms. These are the main elements that stars make, so our pantry has them in relative abundance.

- Every single atom of calcium, sodium, sulfur, chlorine, phosphorus, potassium, and iron comes to us from the later stages of fusion as massive stars flail to keep themselves alive in their dying breaths. The stars don't get much bang for the buck with these stages of fusion, so they produce them in relatively smaller abundances than carbon, nitrogen, and oxygen.

- As for the spices, these rare elements can only be obtained from very special places—the fiery supernovae that are the violent deaths of massive stars. These elements are flash forged in just an instant, and very little of them is produced. Indeed, these are rare spices, but without their seasoning, the recipe of life will fail.

- The stars, both in their lives and in their deaths, make every ingredient in the recipe of life. Through their deaths, they blend these ingredients together throughout the galaxy. Through gravity, they gather up these blended ingredients. And in the course of their struggle to live, they bake that batter to just the right temperature.

- We are made of the stars: We breathe them, we consume them, they course through our veins, and we tingle with them. We live on a world made of them, and we move through a material world built of them. In our contemplations of the stars, in our comprehension of them—indeed, in our very sentience—we are the stars contemplating and comprehending themselves.

Suggested Reading

Darling, *Life Everywhere*.

Gray, *The Elements*.

Questions to Consider

1. If you had to choose, which one element would you regard as the single most important element in the universe, from the standpoint of the "recipe of life"?

2. What other elements might form the basis for life? Can you think of scenarios in which these less abundant elements might be preferred as a basis for life?

A Tale of Two Stars

Lecture 24

This lecture will bring together the essential aspects of the life cycle of stars, personified through a tale of two stars: one like our Sun and one 10 times more massive. The relative masses of these two stars is important because the DNA of the stars, the one thing that determines their life course—from how long they will live to the manner in which they will die—is their mass, their birth weight. Mass is more than destiny for a star; it is fate. The two stars presented in this lecture have very different masses and, therefore, very different fates.

The Stellar Nursery Stage

- Recall that the mass of a star determines everything about it, including its physical properties at every stage of its life, the manner in which it dies, the type of corpse it leaves behind, and, importantly, the types of chemical elements that it can synthesize and return to the cosmos.

- Massive stars live lives that are fast and furious, burning out quickly, leaving behind neutron stars or black holes, but forging in their lives and deaths all of the elements of the periodic table, including the heavy elements that are required for life.

- In contrast to the massive stars, less massive stars—stars like our Sun—live more modestly. They live very long lives, and after they die, their white dwarf corpses are like diamonds in the sky, made of the same carbon that comprises all of life, including our own bodies. Indeed, in their deaths, stars like our Sun gently sprinkle their carbon ashes into the cosmos through majestically beautiful planetary nebulae.

- The two stars in our tale, like all stars, were born in stellar nurseries, enormous clouds of gas and dust that usually weigh about 10,000 times the mass of our solar system. Within stellar nurseries,

hundreds to thousands of individual stars take shape and light up under the influence of gravity, which condenses and collapses the material in the cloud into individual stars.

- Let's imagine that the two stars in our tale are born in the same nursery—they're not siblings, but think of it as if they were born in the same hospital. Of these two stars—the one weighing 1 solar mass or the one weighing 10 solar masses—the more massive one would likely be born first.

- Through their powerful radiation and winds, the most massive stars in the hearts of nurseries exert an enormous influence on the surrounding nursery, weathering and eroding and stripping the surrounding gas and dust and creating the dramatic pillars of creation. In the process, they further compress the material, nudging gravity along and triggering the birth of less massive stars like our Sun within that compressed material.

- What about the planets that will be formed from that protoplanetary disk encircling the Sun-like star? Because the young star is gulping from that disk and will gobble it up in just a few million years, the planet-formation process has a very small window of opportunity to play out. So, just as the smaller star in our tale is getting through its own growing pains, it very quickly has to figure out the challenge of building its own family—and all of this in the dynamic, tumultuous environment of a stellar family, the star cluster, of which the star is but one member.

- Indeed, the Sun-like star in our story is unlikely to be an only child. Most stars like the Sun are not born single; rather, they are typically born with at least one close sibling. So, let's imagine that the Sun-like star in our tale does have a sibling and that this sibling is similar to the Sun-like star but is a bit less massive. How will our star and its sibling influence one another?

- If there are just two siblings, then the two stars will generally leave one another alone, orbiting at a comfortable distance, each capable

of building its own family of planets from its own protoplanetary disk of material. However, if there is a third sibling, a powerful sibling rivalry will play out.

- For the purposes of our tale, let's imagine that our Sun-like star has the lower-mass sibling but not a third. Our Sun-like star and its sibling are part of a larger stellar family, the star cluster of hundreds to thousands of stars all birthed in the same stellar nursery. Even if our two Sun-like siblings treat one another gently, that doesn't mean that the rest of the extended family is going to be so hands-off. However, let's imagine that our Sun-like star manages to avoid the worst consequences of cosmic roughhousing.

- While our Sun-like protagonist has been through all kinds of trouble, our more massive stellar protagonist has been steadily doing its duty, entering the responsibility of adulthood early. Even as the massive star has started the process of nuclear fusion, synthesizing heavier elements in its core, it is taking on a large responsibility for caring for the young stars throughout the stellar nursery and establishing the foundations for the extended stellar family.

- As the family of stars leaves the nursery after about 50 million years, it is a full-fledged cluster, leaving its breeding grounds to join the rest of the galaxy. And just as the extended stellar family moves on, the massive star in our tale is preparing to end its life in dramatic fashion. The massive star quickly goes through the various stages of nuclear fusion.

- With each round of fusion, the massive star in our tale is resuscitating itself for briefer and briefer periods of time. Finally, once our massive star protagonist has fused all the way to iron in the core, its beating heart comes suddenly and tragically to a halt, for good, a little more than about 100 million years into its life.

- Perhaps morbidly, the massive star in our story dies in a violent supernova explosion in full view of the rest of its extended family of stars in its cluster. Its core collapses down to an unimaginably

dense neutron star, and as the rest of its hulking body implodes onto that neutron star at its center, that material bounces off and explodes into the surrounding space with an energetic brilliance unmatched anywhere in the galaxy—indeed, in the whole universe. At that moment, in the fireball of the supernova, all of the rest of the elements of the periodic table are flash forged.

- These elements—indeed, all the elements forged over the life of this massive star—are now scattered throughout the stellar cluster. The blast wave of the supernova pushes a supernova remnant, a hot expanding bubble of gas and ash, beyond the extended family of stars in this one cluster and out into the surrounding galactic medium. It even carves a chimney up out of the galaxy and sends its ashes like a geyser into the halo of the galaxy.

- That material finally rains back down throughout the galaxy, sprinkling the dead star's ashes everywhere. In its superlative death, our massive star protagonist provides a sort of manna from heaven, in the form of gas and ash enriched in all of the elements of the periodic table, from which new generations of stars and planets may form, enhanced in their ability to create and sustain life.

- In the outskirts of the cluster where the massive star exploded, the shockwave of its expanding supernova remnant may compress and heat the gas and dust in the surrounding space, directly triggering and fertilizing a new stellar breeding ground.

- In the wake of this incredible event, the Sun-like star in our tale is perhaps a light-year away from the massive star that exploded. Still residing in the stellar family that is a few light-years across overall, it goes on about the business of growing up and starting its own solar system. Little by little, our Sun-like protagonist grows up, gradually growing apart from the rest of its extended family and eventually establishing its own place with its young solar system in the larger galaxy.

The Adult Stage

- Our Sun-like star enters the long stage of middle life. As a young adult, the star jumps straight into the responsibility of hard work, fusing hydrogen in its core into helium. Those early fruits of its labors may not be worth much in and of themselves, but the true value of those labors is in the foundation that these products will provide in the later stages of the star's adulthood to create true wealth—in the form of carbon.

- As a young adult, the star is full of vim and vigor; it spins rapidly. Its magnetic field, generated in the dynamo action of its rapid spin, lurches and occasionally erupts in fits of rage that the star will reign in as it continues to mature and slows down a little bit.

- These bursts of magnetism, which shower the orbiting planets with intense X-rays, might be essential to spur on early biogenesis. They may also have a profound effect on nascent life forms on one or more of those planets by promoting the types of rapid mutations that lead to the proliferation of life in all its varieties.

- As the adult star ages and as its system of planets enters its own stable state, the star gradually winds down, its space weather becoming gentler—though with occasional stern reminders. Meanwhile, its vital signs, as measured through its sunquakes and the neutrinos that it puts out, clearly indicate that fusion continues strong and steady in its core.

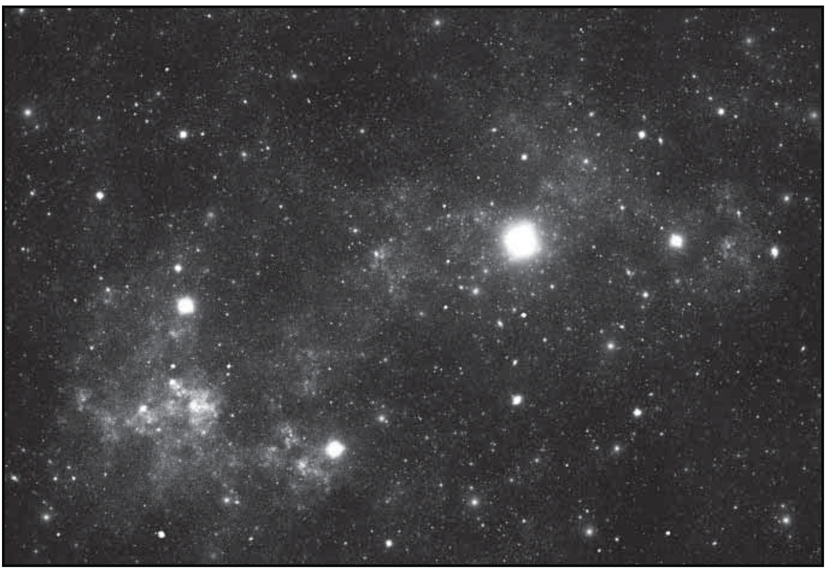
- Then, suddenly, when the star is about 10 billion years old, the star experiences the equivalent of a severe cardiac arrest as it completes its task of fusing the hydrogen in its core completely to helium. And at that moment, gravity pounces, collapsing the core toward oblivion.

- But this star is not done yet. The core heats up hotter and hotter under the crush of gravity, until it reaches about 100 million degrees. At that temperature, the core can start the process of fusing

helium into carbon. So, the star resuscitates as a red giant. Overall, the star is cooler now, yet it shines more brightly than before, having swelled in size 100-fold.

- This is an elderly parent, still glowing with life, knowing that it is banking up the wealth for the next generation that it had prepared for throughout its life—storing up entire worlds worth of carbon, the stuff of life. The process of fusing helium to carbon lasts a relatively short time—perhaps no more than 1 billion years for a star with the mass of the Sun.

- Finally, after a long life of about 10 billion years, our red giant protagonist, ringed by its stellar sibling and its planetary children, lying still and short of breath, reveals the inheritance that it has in store. This Sun-like star cannot initiate another round of nuclear fusion. It simply doesn't have the mass that would allow it to



Only a very small percentage of the many, many trillions of stars that exist in the universe is visible to the naked eye.

generate a sufficient temperature. The star's mass dictating its fate, it is doomed now to die.

- As it breathes its last, it returns itself whence it came, a quiet but beautiful and graceful planetary nebula sprinkling its carbon ashes like rich seeds of potential for future generations. And for a time, the grave marker of the star is fresh and gleaming—a white dwarf, a tiny but white-hot diamond of a corpse. The star will now only fade into the ages, forever cooling, dimming, and eventually becoming a black dwarf, inert and still and dark.

- The star's sibling has been aging and tending its own, too. It was a bit less massive than our Sun-like star, which means that it will live longer. Even so, it too is destined to die. And when its time comes, it too will swell into a red giant as it enters its second-wind stage of fusing helium to carbon. But the sibling's experience as a red giant will be quite different.

- As this red giant swells and comes into proximity with its now long-dead sibling, the red giant transfers some of its mass onto the white dwarf, slowly building up the white dwarf's heft to the breaking point. The white dwarf collapses and produces a white dwarf supernova.

- Both of our story's protagonists are notable for their steadfast commitment throughout their lives—one brief, one long—to hold strong against gravity long enough to produce a legacy for the subsequent generation and beyond. Indeed, our story doesn't end so much as mark the new beginning of those next generations of stars.

Suggested Reading

Kippenhahn, *100 Billion Suns*.

Lang, *The Life and Death of Stars*.

Questions to Consider

1. Which types of stars—stars less massive than the Sun or stars more massive than the Sun—are the most likely likely to harbor long-term habitable planets?

2. With which type of star—a star like our Sun or a star much more massive—do you identify with most, in terms of the experience of the circle of life?

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